# Functional space-time properties of team synergies in high-performance football

**Nelson Candido Andrade Caldeira**

Orientadores: Prof. Doutor Duarte Fernando da Rosa Belo Patronilho de Araújo
Prof. Doutor Rui Jorge Henriques Calado Lopes

Tese especialmente elaborada para a obtenção do grau de doutor em Motricidade Humana, na Especialidade de Treino Desportivo

**2023**

ULISBOA | UNIVERSIDADE DE LISBOA

fMH FACULDADE DE MOTRICIDADE HUMANA

# Functional space-time properties of team synergies in high-performance football

**Nelson Candido Andrade Caldeira**

Orientadores: Prof. Doutor Duarte Fernando da Rosa Belo Patronilho de Araújo
Prof. Doutor Rui Jorge Henriques Calado Lopes

Tese especialmente elaborada para a obtenção do grau de doutor em Motricidade Humana, na Especialidade de Treino Desportivo

**Júri**

Presidente: Prof. Doutor António Prieto Veloso
Vogais: Prof. Doutor Duarte Fernando da Rosa Belo Patronilho de Araújo
Prof. Doutora Anna Georgievna Volossovitch
Prof. Doutor Pedro José Madalena Passos
Prof. Doutora Sofia Cristina Carreiras Fonseca
Prof. Doutor Pedro Miguel Moreira Oliveira e Silva

**2023**

*Em memória dos meus pais*
*Basílio e Luísa Caldeira*

# Acknowledgements

Na conclusão desta tese gostaria de agradecer em primeiro lugar à minha família que apoiou incondicionalmente a ideia deste projeto. À Paula, ao Nelson, à Isabel e à Catarina, agradeço terem compreendido e aceitado ficar sem a atenção devida. Tanto nas inúmeras horas de convívio familiar de que lhes privei da minha presença, como no silêncio que lhes solicitava em tantas outras para poder avançar na leitura e na escrita desta tese.

Agradeço ao professor doutor Duarte Araújo o ter aceitado orientar esta tese, mesmo sabendo que teria a ingrata missão de procurar transformar num projeto de tese um conjunto de ideias mais ou menos dispersas de um treinador. Agradeço a sua disponibilidade e paciência para tentar tirar algum sumo das enormes quantidades de texto que lhe fui propondo, na minha ânsia de responder aos problemas que o assunto da tese me suscitava. Mas sobretudo por ampliar enormemente os meus conhecimentos, despertando-me para conceitos e esclarecendo tantos outros. Na sua articulação coerente de conceitos, perspetivas e reflexões, o seu impacto na minha vida profissional enquanto treinador ultrapassa em muito o âmbito desta tese e só posso estar imensamente agradecido.

Agradeço ao professor doutor Rui Jorge Lopes, que aceitando ser co-orientador desta tese, foi demonstrando na prática de todos os dias o alcance do conceito de sinergia e o seu impacto na vida humana. Ao aluno não teria sido de todo possível avançar até aqui, se não tivesse a cooperação sempre pronta e totalmente disponível para o que fosse necessário do professor. Bem como se não me tivesse lançado os desafios mais incríveis, mesmo sabendo que na sua frente estava um simples treinador de futebol. As suas muitas ideias, conceções, métodos e ferramentas, demonstraram um poder imenso de retirar informação altamente qualitativa do contexto de jogo, pelo que me sinto um enorme privilegiado pela oportunidade de ter tido a sua orientação. Por isso, estou muitíssimo agradecido por todo o tempo e sabedoria que dedicou a esta tese e pelas extraordinárias aprendizagens que ficam para a vida.

Um agradecimento especial tenho de deixar ao engenheiro Dinis Fernandes, que aceitou ser co-autor em alguns dos trabalhos desta tese e que muito contribuiu para avançarmos na quantificação espaço-temporal das interações dos jogadores. O que começou por ser uma colaboração voltada para o âmbito estrito do futebol profissional, no desenvolvimento de software específico para o tratamento dos dados posicionais recolhidos em competição, acabou por dar origem aos dados que foram aqui utilizados nesta tese. Tenho de enaltecer a qualidade do seu trabalho e a disponibilidade para ir incluindo nas ferramentas informáticas as ideias que foram resultando do avançar dos trabalhos e da reflexão sobre o jogo, construindo uma parceria que fica para a vida e de que serei sempre grato.

Um agradecimento especial para todos os treinadores que tiveram a amabilidade e a paciência de fazer parte dos ”painéis de especialistas” nos capítulos 6 e 7. Não posso deixar de referir nesta secção de agradecimentos, a marca de todos aqueles que contribuíram indiretamente para esta tese, mesmo sem disso terem consciência. Ao serem tantos não seria possível os nomear devidamente. Desde todos aqueles que contribuíram pela minha paixão inicial pelo jogo enquanto praticante da modalidade (os meus irmãos e irmãs, amigos de infância, colegas de equipas federadas e amadoras, treinadores, etc.). A todos aqueles com quem tenho contactado ao longo desta vida profissional de quase três décadas como treinador e que muito me ensinaram sobre o futebol e o seu treino (jogadores, treinadores, dirigentes, etc.). Sem esquecer todos os colegas e professores destes três ciclos universitários que agora se concluem. Tanto na licenciatura na Universidade da Madeira, no mestrado na Universidade do Porto e agora neste doutoramento na Universidade de Lisboa, a todos o meu muito obrigado.

# Abstract

This thesis aimed to investigate the performance of high-level teams in football, through the analysis of the interactions of their players in the context of the game, as these interactions result in *functional effects* that could not otherwise be achieved (synergies).

From a spatial point of view, we argue that the understanding of collective "*payoffs*" emerging from players' interactions and their behavioural patterns, can be accomplished through "*Delaunay triangulations*" and consequent "*Voronoi diagrams*". Analysing the positional data (22 players and the ball) in 20 games of the French premier league, in this thesis we essentially sought to focus on *territorial dominance* as a variable that potentially captures the spatial affordances perceived by players. Whether from a collective *global* point of view or from a perspective of the *local* interactions that arise in the game landscape.

Supported by the *ecological dynamics* and the *synergism hypothesis*, in this thesis we begin by demonstrating the existing connection between the *territorial dominance* of a team and the offensive *effectiveness*, as well as the absence of temporal overlap between the *ball possession* status and *territorial dominance*. Similarly, we also demonstrated that the *space dominance* of each player, which contributes to the *territorial dominance* of the team as a whole, is constrained by the *team's formation* and the *role* assumed by each player in this collective framework.

In order to understand the dynamics of interactions between players and the functional effects that come from it, we then focus on two tasks that are related to collective performance: the pass and the shot. Reflecting on the need to find methods that capture how the *distribution* of players on the pitch influences the *functional degrees of freedom* of a team as a whole and the passing opportunities that emerge from it. And, at the level of finishing situations, how the dominance of space can be included in the quantification of the *value* that each player assigns to occupy a certain place in the game landscape, and which is at the basis of their decision-making (shoot or pass the ball to another teammate possibly better "positioned").

In sum, through the initial conceptual framework and the applied studies, we argue that the analysis of team performance should focus on the functional synergies that result from interactions between players. In this way, we demonstrate, through some examples, how the methods and conclusions taken from this thesis can be applied in practice by football coaches.



**Keywords:** Affordances, Delaunay triangulations, Players' interactions, Space dominance, Voronoi diagrams

# Resumo

Esta tese teve como objetivo investigar a performance de equipas de alto nível no futebol, através da análise das interações dos seus jogadores no contexto do jogo pois daí resultam *efeitos funcionais* que apenas são atingidos através dessas mesmas interações (sinergias). De um ponto de vista espacial, defendemos que o estudo *glocal* das interações entre os jogadores para a compreensão do rendimento coletivo, pode ser realizado através de "*triangulações de Delaunay*" e consequentes "*diagramas de Voronoi*". Analisando os dados posicionais dos 22 jogadores e da bola, em 20 jogos da primeira liga francesa, nesta tese procurámos essencialmente nos focar sobre o *domínio territorial* enquanto variável que capta potencialmente as *affordances* espaciais percebidas pelos jogadores. Seja de um ponto de vista *global* coletivo, seja numa perspetiva das interações *locais* que surgem na paisagem de jogo.

Suportados pela *dinâmica ecológica* e pela *hipótese do sinergismo*, nesta tese começamos por demonstrar a ligação existente entre o *domínio territorial* das equipas e a sua *efetividade* ofensiva, bem como a inexistência de uma sobreposição temporal entre a posse de bola e esse domínio. De igual forma, também demonstrámos que o *domínio do espaço* de cada jogador, que contribui para o domínio territorial da equipa no seu todo, é constrangido pelo sistema de jogo das equipas e pelo papel assumido por cada jogador neste referencial coletivo.

No sentido de compreender a dinâmica das interações entre os jogadores e os efeitos funcionais que daí advêm, focamo-nos seguidamente em duas tarefas que estão relacionadas com a performance coletiva: o passe e o remate. Refletindo sobre a necessidade de encontrar métodos que captem de que forma a distribuição dos jogadores em campo influencia os graus de liberdade funcionais de uma equipa no seu todo e as oportunidades de passe que daí emergem. E, ao nível das situações de finalização, de que forma o *domínio do espaço* poderá ser incluído na quantificação do valor que cada jogador atribui a ocupar um determinador espaço na paisagem de jogo e que está na base da sua tomada de decisão (rematar ou passar a bola para outro colega eventualmente melhor "posicionado").

Em suma, através do enquadramento conceptual inicial e dos estudos aplicados, defendemos que o estudo da performance das equipas deverá se centrar nas sinergias funcionais que resultam das interações entre os jogadores. Desta forma, demonstramos, através de alguns exemplos, como é que os métodos e ilações retirados desta tese poderão ser aplicados na prática pelos treinadores de futebol.

## Resumo desenvolvido

Esta tese teve como objetivo investigar a performance de equipas de alto nível no futebol, através da análise das interações dos seus jogadores no contexto do jogo. Baseamo-nos na ideia de que a performance das equipas no seu todo tem a sua expressão mais geral nos seus resultados (por exemplo, a vitória num jogo ou a classificação num campeonato). No entanto, essa performance da equipa facilmente mensurável não pode ser explicada linearmente pela soma da (micro) performance de cada um dos seus jogadores. Assim, defendemos nesta tese a ideia de que a performance da equipa emerge de um complexo emaranhado de interações entre os jogadores em campo, que resultam em efeitos funcionais que apenas são atingidos através dessas mesmas interações (sinergias).

Defendemos que devido ao valor neutro do conceito de sinergia em sentido lato, o estudo dos padrões comportamentais que emergem dessas sinergias levará a compreender melhor a performance das equipas de futebol, seja o rendimento (payoff) que resulta das interações positivo, negativo ou neutro. Desta forma, esta tese pretende contribuir para compreender as sinergias funcionais das equipas de futebol que emergem das interações entre os jogadores quando pretendem realizar uma determinada tarefa (por exemplo, manter a posse da bola, ou fazer / evitar um golo).

É certo que devido à dinâmica caótica do jogo de futebol, o desempenho de uma equipa na realização de uma dada tarefa também não explica linearmente o (macro) resultado de um jogo. Mas não é menos verdade que esse resultado depende da capacidade das equipas em realizar essas tarefas coletivas. Assim, a escala (meso) que se centra sobre as interações entre os elementos da equipa e as sinergias que daí resultam na realização de uma dada tarefa de jogo, é a escala onde treinadores e investigadores mais devem se concentrar. Esta perspetiva implica um olhar *glocal* sobre o processo de treino e de análise das equipas, compreendendo a influencia bidirecional entre o global (a equipa) e o local (e.g., a interação entre dois jogadores através de um passe).

No entanto, um olhar *glocal* sobre a performance levou-nos a constatar o carácter demasiado redutor de algumas abordagens quantitativas (e.g., baseadas no estudo de díades), mas também o demasiado holístico de outras (e.g., no estudo dos centroides das equipas). Neste contexto, despertou-nos interesse pedagógico e científico as medidas de divisão da globalidade do espaço de jogo, através da deteção (local) das relações de proximidade entre cada jogador e os seus "vizinhos". Daqui surgiu a ideia de utilizarmos "triangulações de Delaunay" e consequentes "diagramas de Voronoi" para estudar *glocalmente* as sinergias que advêm das interações dos jogadores.

Assim, nesta tese analisamos os dados posicionais dos 22 jogadores e da bola, em 20 jogos da primeira liga francesa, para realizar os quatro capítulos que constituem a investigação aplicada desta tese. Em todos eles é comum a investigação em torno do "domínio territorial" enquanto variável que capta potencialmente as affordances espaciais percebidas pelos jogadores. Seja de um ponto de vista global coletivo (nos capítulos 4 e 5), seja numa perspetiva das interações locais que surgem na paisagem de jogo (nos capítulos 6 e 7).

Depois de nos capítulos 2 e 3 fundamentarmos conceptualmente esta perspetiva de que o estudo da performance das equipas de futebol de alto nível deve se basear na análise das sinergias e que as mesmas podem ser captadas por medidas espaço-temporais, no capítulo 4 abordamos a importância do domínio territorial das equipas na sua efetividade ofensiva. Isto foi realizado comparando os "episódios de posse de bola" (PE) em que as equipas conseguem atingir situações de finalização ou pré-finalização (efetivos) com aqueles em que não o conseguem fazer (não efetivos). Utilizámos comparativamente para tal duas variáveis: a "soma das áreas de Voronoi" (SVA) e os "convex hull" das duas equipas em confronto. Considerámos que estas variáveis coletivas, que já tinham sido apontadas na literatura como indicadores para o domínio territorial das equipas no seu todo, "comprimem dimensionalmente" todas as interações espaciais dos jogadores em campo. Verificámos neste estudo que a SVA, que advém da simples soma das áreas (em m2) das células de Voronoi de todos os elementos de uma equipa, é uma variável com significativa sensibilidade para discernir os PE efetivos dos não efetivos. E essa sensibilidade da SVA não é apenas detectável no instante final dos PE como também, embora em menor grau, no instante em que as equipas recuperaram a posse da bola. Ou seja, os PE efectivos mostraram uma tendência clara para serem iniciados já com "domínio territorial", que se podia observar também na fase em que as equipas ainda não tinham a posse da bola. Desta forma, para além da comprovada ligação entre o domínio territorial das equipas e a sua efetividade ofensiva, ficou demonstrado que os conceitos de "posse de bola" e "ataque" não são sinónimos e não devem ser utilizados como tal. Em suma, atacar a baliza do adversário é, pelo menos no jogo de alto nível, uma expressão da intenção ofensiva das equipas, detectável sobretudo no seu "domínio territorial" (SVA) e esta pode se iniciar comprovadamente antes da recuperação da posse de bola.

Ainda numa escala essencialmente global das equipas, mas sem perder o contexto local em torno do portador da bola, o capítulo 5 consubstancia uma proposta de quantificação dos "graus de liberdade funcionais" para o passe. Neste sentido, defendemos que o estudo da distribuição dos jogadores em campo e das configurações que uma equipa pode cristalizar num determinado instante, deve ser feito através de um referencial dinâmico e não através da divisão do campo em zonas fixas. Neste sentido, propusemos um esquema de análise das "oportunidades de passe" que são oferecidas ao portador da bola (affordances) pelos seus colegas, que se compensam reciprocamente através dos seus deslocamentos em campo. Este esquema baseia-se na divisão do espaço efetivo de jogo em 12 zonas dinâmicas, definidas por intermédio do posicionamento relativo das células de Voronoi de cada jogador, tendo por referência o centroide do jogo. Através deste esquema, é captado o comportamento cooperativo coletivo de uma equipa no contexto de jogo, podendo ser analisado de forma objetiva em cada instante mas também mostrar padrões em diferentes escalas temporais. Neste capítulo (bem como nos exemplos práticos do capítulo 8), demonstrámos praticamente a utilidade desta "prova de conceito".

No capítulo 6, o foco da nossa análise passou a se centrar na influência que os constrangimentos globais de uma equipa podem ter sobre os padrões observáveis ao nível do "domínio do espaço" de cada jogador individualmente. Neste caso analisamos o sistema de jogo ou "team formation (TF) das equipas e os respetivos papéis (PR) que são atribuídos a cada jogador. Verificámos neste estudo que existem diferenças significativas nos padrões espaciais individuais que emergem da colaboração dos jogadores, "dividindo o trabalho" na realização das suas tarefas coletivas (tendo ou não a posse da bola). Assim ficou demonstrado que o "domínio do espaço" individual dos jogadores (que contribui para o "domínio territorial” da equipa no seu todo), depende do seu “papel” em cada TF, nomeadamente do sector onde habitualmente se encontram (defesas, médios ou atacantes) e a sua posição relativa no espaço efetivo de jogo (interior ou exterior).

Finalmente ao nível da investigação aplicada, no capítulo 7 analisamos de que forma o “domínio do espaço” dos jogadores envolvidos em situações de finalização, poderia constranger a tomada de decisão do portador da bola sobre rematar ou passar. Neste estudo, utilizámos um modelo baseado na mensuração da área das células de Voronoi e da posição relativa dos jogadores dentro das respetivas células e em relação à baliza adversária (distância e ângulo para o centro da mesma). Calculando um “Valor do Espaço para a Finalização” (FSV), este modelo procurou captar potenciais affordances percebidas pelos jogadores a dois níveis espaciais fundamentais: a) até que ponto a baliza seria alcançável com sucesso por um remate; b) até que ponto existe espaço suficiente para rematar. Estas questões operacionais consideram o local onde está cada elemento no contexto da situação de jogo permitindo calcular um FSV para cada jogador, que traduzisse a escolha degenerada da equipa para executar a função (rematar). Os resultados deste modelo foram comparados com a opinião subjetiva de um painel de treinadores especialistas. Foi constatada a adequação do mesmo em captar na paisagem de jogo os parâmetros espaciais que mais podem influenciar a tomada de decisão do portador da bola no contexto de situações de finalização.

Em suma, através do enquadramento conceptual inicial e dos estudos aplicados acima descritos, defendemos que a performance das equipas de alto nível poderá ser analisada através das sinergias funcionais que resultam das interações entre os jogadores (colegas e adversários). Mais defendemos que essas sinergias podem ser captadas de um ponto de vista funcional, através dos dados posicionais recolhidos pelos sistemas de tracking cada vez mais frequente em contexto de treino e competição (GPS, optical sensors, etc.). Esta perspetiva é ilustrada através da exemplificação prática realizada nos últimos capítulos (8 e 9), procurando fazer uma ponte entre as ilações que emergiram da análise dos dados quantitativos e a prática dos treinadores.

**Palavras-Chave:** Affordances, Delaunay triangulations, Players’ interactions, Space dominance, Voronoi diagrams

# Contents

**Contents** xiii

**List of Figures** xix

**List of Tables** xxiv

**1 General Introduction** 2

1.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 3

1.2 Outline of the present thesis . . . . . . . . . . . . . . . . . . . . . . . . . 4

1.2.1 General Introduction . . . . . . . . . . . . . . . . . . . . . . . . . 4

1.2.2 How the synergism hypothesis, aligned with an ecological dynamics' perspective, can underpin the research of high-level football teams' performance . . . . . . . . 5

1.2.3 Using Voronoi diagrams to assess high-performance football team synergies . . . 6

1.2.4 Team's global quest for territorial dominance . . . . . . . . . . . . . . 7

1.2.5 Passing affordances are constrained by players' distribution on the field, i.e., by the team's functional degrees of freedom . . . . . . . . . . . . . . 7

1.2.6 The specific contribution of each player to dominate the playing pitch . . . . . . . . 7

1.2.7 Understanding players' shooting degenerate decision-making . . . . . . . . . . . . 8

1.2.8 A possible coach's perspective on the performance analysis of the in-possession football team supported by Voronoi diagrams . . . . . . . . . . 8

1.2.9 Performance analysis of the out-of-possession football team supported by Voronoi diagrams . . . . . . . . . . . . . . . . . . . . . . . . 9

1.2.10 General discussion . . . . . . . . . . . . . . . . . . . . . . . . . . 9

References . . . . . . . . . . 10

**2 How the synergism hypothesis, aligned with an ecological dynamics' perspective, can underpin the research of high-level football teams' performance** **13**

2.1 Keywords . . . . . . . . . . 14

2.2 Introduction . . . . . . . . . . 15

2.3 An ecological dynamics approach to collective performance . . . . . . . . . . 16

2.4 The "synergism hypothesis" and the football performance . . . . . . . . . . 17

2.4.1 The concept of synergies in the human movement science . . . . . . . . . . 17

2.4.2 A broad concept of synergies to understand football performance . . . . . . . . . . 18

2.5 The "synergism hypothesis" and the team sports' research . . . . . . . . . . 20

2.6 Reductionist and holistic methods to investigate football team synergies . . . . . . . . . . 23

2.6.1 A "synergetics" reductionist approach to team sports synergies . . . . . . . . . . 24

2.6.2 A holistic approach to team sports synergies based on the "Synergetics" . . . . . 24

2.6.3 Compound physical variables to holistically assess team sports synergies . . . . . 25

2.7 Present and future challenges to test the "synergism hypothesis" in football . . . . . . . . 27

References . . . . . . . . . . 30

**3 Voronoi diagrams as a means to capture football team's synergies: from positional data to match analysis and training design** **42**

3.1 Introduction . . . . . . . . . . 44

3.2 Quantification methods to assess teams' synergies . . . . . . . . . . 44

3.3 Synergistic properties captured through Voronoi diagrams . . . . . . . . . . 45

3.4 Using Voronoi diagrams (VD) to assess physical and social interactions . . . . . . . . . . 46

3.4.1 Voronoi diagrams to assess human interpersonal interactions . . . . . . . . . . 47

3.4.2 Using Voronoi diagrams to program the interactions of autonomous robots . . . . . 48

3.5 How Voronoi diagrams can be used to assess football team's synergies? . . . . . . . . . 48

3.5.1 The assessment of sport team's interpersonal linkages by Voronoi Diagrams . . . 49

3.5.2 The assessment of dimensional compression by Voronoi Diagrams . . . . . . . . . 50
3.5.3 The assessment of reciprocal compensation through Voronoi Diagrams . . . . . . 51
3.5.4 The assessment of degeneracy through Voronoi Diagrams . . . . . . . . . . . . 52
3.6 Conclusion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 53
References . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 54

**4 Team's territorial dominance in high-performance football: ball possession should not be mistaken with attacking 65**

4.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 67
4.1.1 The concept of *territorial dominance* . . . . . . . . . . . . . . . . . . . . . . . 67
4.1.2 Territorial dominance, ball possession and attacking effectiveness . . . . . . . . . 68
4.1.3 The assessment of the territorial dominance in football . . . . . . . . . . . . . . . 69
4.2 Materials and Methods . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 70
4.2.1 Data sources . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 70
4.2.2 Data processing . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 71
4.2.3 Statistical analysis methods . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 72
4.3 Results . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 73
4.3.1 CH and SVA differences according to teams' ball possession status . . . . . . . . 74
4.3.2 CH and SVA differences according to ball possession episode effectiveness . . . 75
4.4 Discussion and Conclusions . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 77
References . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 85

**5 A dynamic method based on Voronoi-diagrams to assess the collective functional degrees of freedom of team passing behaviour in high-performance football 89**

5.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 91
5.1.1 Football team's functional degrees of freedom . . . . . . . . . . . . . . . . . . . 92
5.1.2 The assessment of ecologically defined players' distribution on the pitch . . . . . . 94
5.2 Materials and Methods . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 95

5.2.1 Data sources . . . 95
5.2.2 Data processing . . . 96
5.3 Results . . . 100
5.3.1 Single instant analysis . . . 100
5.3.2 Two successive passing events analysis . . . 102
5.3.3 Successive periods analysis: halves of a match . . . 103
5.4 Discussion . . . 105
5.5 Conclusion . . . 106
References . . . 108
**6 From optical tracking to tactical performance via Voronoi diagrams: team formation and players' roles constrain interpersonal linkages in high-level football 113**
6.1 Introduction . . . 115
6.2 Materials and Methods . . . 116
6.2.1 Data sources . . . 116
6.2.2 Data processing . . . 117
6.2.3 Statistical analysis methods . . . 118
6.3 Results . . . 119
6.3.1 Comparing players' VA within the same team formation . . . 120
6.3.2 Comparing players' VA between different team formations . . . 122
6.4 Discussion . . . 123
6.5 Conclusion . . . 125
References . . . 127
**7 The Finishing Space Value for shooting decision-making in High-Performance Football 130**
7.1 Introduction . . . 131
7.1.1 Players' decisions and actions are guided by their perceived *affordances* . . . 131
7.1.2 Collective decisions in finishing situations . . . 132

7.1.3 Developing a method to capture spatial affordances in finishing situations . . . . . 133
7.1.4 The “Finishing Space Value” (FSV) model for decision-making to shoot . . . . . . 135
7.2 Materials and Methods . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 137
7.2.1 Data sources . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 137
7.2.2 Data processing . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 139
7.2.3 Statistical analysis methods . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 144
7.3 Results . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 146
7.3.1 Comparative analysis of the ball carrier’s probability to score . . . . . . . . . . . . 146
7.3.2 The coaches’ ”Panel of Experts” (PE) opinion . . . . . . . . . . . . . . . . . . . . . 146
7.3.3 Comparative analysis between the PE and the FSV model . . . . . . . . . . . . . . 147
7.4 Discussion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 149
7.4.1 Limitations and future work . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 151
7.4.2 Practical applications . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 151
References . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 169

**8 Performance analysis of the *in-possession* football team supported by Voronoi diagrams 175**

8.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 176
8.2 Quantifying the ball carrier spatial landscape . . . . . . . . . . . . . . . . . . . . . . . . 176
8.3 Understanding the ball carrier’s teammates’ tactical problems . . . . . . . . . . . . . . . 179
8.4 The global (self-)-coordination of the *in possession* team . . . . . . . . . . . . . . . . . 181
8.5 Conclusion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 187
References . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 188

**9 Performance analysis of the *out-of-possession* football team supported by Voronoi diagrams190**

9.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 191
9.2 Team coordination during a “high-pressing” tactical-strategy . . . . . . . . . . . . . . . . 192
9.3 An individual tactical dilemma of a central defender . . . . . . . . . . . . . . . . . . . . . 198

9.4 Conclusion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 199

References . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 202

**10 General discussion and future research** **204**

10.1 General discussion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 205

10.2 Practical implications and thesis limitations . . . . . . . . . . . . . . . . . . . . . . . . . 207

10.3 Future research . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 209

References . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 212

# List of Figures

3.1 One-time frame Voronoi diagram. *Example of Voronoi diagram (VD) with players' Voronoi cells (red and blue polygons), in a match frame. Compound variables can be extracted from the VD and other metrics, e.g., match and teams' centroids (yellow, blue and red crosses) or the match (dashed yellow polygon) and team's convex hull (dashed red polygon for the in possession and dashed blue polygon for the out of possession team).* . . . . . . . . . 49

4.1 One time frame Voronoi diagram and convex hulls. *Voronoi diagram players' cells (red and blue polygons); match and teams' centroid (yellow, blue and red crosses); convex hull for the match (dashed yellow polygon), in possession team (dashed red polygon) and out of possession team (dashed blue polygon).* . . . . . . . . . . . . . . . . . . . . . . . . . 72

4.2 $SVA$ and $CH$ time-series during a PE, for the teams *in possession* and *out of possession* 73

4.3 Violin plots of CH and SVA areas according to ball possession status . . . . . . . . . . . . 74

4.4 Forest plot of the effect size of the differences of $CH$ and $SVA$ areas, according to ball possession status . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 74

4.5 Comparison of $CH$ and $SVA$ areas according to ball possession effectiveness ($Np$ vs $Ep$). 76

4.6 Forest plot of the effect size of the CH and SVA differences by possession episodes effectiveness (Np vs Ep) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 77

4.7 ApEn comparison of CH and SVA according to ball possession effectiveness (Np vs Ep). . 78

4.8 Forest plot of the effect size of the differences by possession episodes effectiveness (Ep vs Np), for the ApEn of teams' SVA and CH time-series . . . . . . . . . . . . . . . . . . 79

5.1 An example of the division of the EPS in a set of 12 dynamic zones, using the match centroid and Voronoi diagrams for one frame. *Note: Voronoi diagrams with the cells of each player identified by a number. In the diagram is highlighted: a) the match centroid (black cross); b) the teams' centroids (red and blue crosses); c) the match effective play-space (dashed yellow polygon); d) teams' convex hull (blue and red dashed polygons)* . . . . . . . 97

5.2 Division of the EPS into twelve zones: schematic representation (a) and illustrative example (b). . . . . . 99

5.3 Assessing the teams' zonal balance . . . . . 99

5.4 Team's fDOF and team's zonal balance during a pass event ($t = 449.6s$) *Note: a) Number of the in-possession team's functional degrees of freedom (fDOF, i.e., the number of quadrants and octants that are not empty); b) Identification of the player with the ball, her/his tactical mission (in this case right winger, RW) and her/his Voronoi cell Area ($m^2$); c) Offensive Distance (OD) to the opponent's goal (meters); d) Ball carrier coordinates (longitudinal, x and lateral, y); e) Pass with (CONT) or without (NO CONT) continuity; f) Number of team players in each zone, where* $0 \equiv$ *White,* $1 \equiv$ *Green,* $2 \equiv$ *Yellow and* $\geq 3 \equiv$ *Red; g) Numerical balance between teams in that zone, where* $< 0 \equiv$ *Red;* $0 \equiv$ *Yellow;* $> 0 \equiv$ *Green; h) Number of the pass event in the match; i) Zone where is the Ball (ball carrier); j) Identification of the instant in the match (seconds); k) Possession episode (PE) with (YES) or without (NO) a finishing event (and the duration of the PE, in seconds); l) Identification of the Team, the venue context (Home or Away) and the current result (draw, winning or losing).* . . . . 100

5.5 Team's fDOF and team's zonal balance, dynamics between two passing events (Pass 68 at $t = 449.6s$ and Pass 69 at $t = 452.7s$) (see text for details) . . . . . 102

5.6 Exemplar comparison of the occupation frequency in each EPS zone, in two halves of a match (see text for details) . . . . . 103

6.1 Voronoi diagrams for analysed teams (blue) in two team formations (a. 4-2-3-1 and b. 3-4-1-2) and the opposing team (red) . . . . . 119

6.2 Players' Voronoi area probability density function in the 4-2-3-1 team formation. *Note:* Violin plots (a) and heatmaps (b and c) comparing players' Voronoi area probability density function (less similar in blue, more similar in red). The differences that are statistically not relevant are highlighted in **bold**) . . . . . 121

6.3 Players' Voronoi area probability density function in 3-4-1-2 team formation. *Note:* Violin plots (a) and heatmaps (b and c) comparing players' Voronoi area probability density function (less similar in blue, more similar in red). The differences that are statistically not relevant are highlighted in **bold**) . . . . . 122

6.4 Comparison of the VA of players' roles in both team formations . . . . . 123

7.1 Illustrative image of a finishing situation presented in the survey to the "panel of expert" football coaches. Player "A" is the ball carrier who shot and the players marked with B, C and D are his colleagues that we consider as possible passing options. . . . . . 139

7.2 Shots with (blue) and without (red) scoring according to distance and angle to goal. . . . . 140

7.3 Player's Voronoi cells in four different regions of the effective playing space (EPS) *Note:* Voronoi diagram with the positions of players from both teams: the "in ball possession" team (red circles) and the "out of ball possession" team (blue circles). The Effective Playing Space (EPS) is limited by the yellow dashed line. Four regions were identified: inside the EPS (INS) or outside the EPS, in this case considering three different situations (i.e., OUT_S, OUT_F; OUT_S_F). Crosses indicate the match (yellow) and the team's centroids (red and blue). See text for details. . . . . . . 142

7.4 Voronoi diagrams with different distances to the nearest defender . . . . . . . . . . . . . . 143

7.5 Linear regression between the result of the FSV and the subjective perception of the Panel of Experts (PE) about the "probability to score from a shoot" of the player's "A" (the ball carrier), in each finishing situation . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 146

7.6 Histogram with the values of the Gwet's agreement coefficient. It shows the frequency of the situations where the PE did not minimally agree (black, No majority) and the frequency with which the PE produced a tendency in their answers, in the sense that the "best option" to shoot would be: 1) the ball carrier (green, option A); 2) one of his teammates (brown, options B, c or D); 3) Other option (red, E) . . . . . . . . . . . . . . . . . . . . . . . . . 147

7.7 Graph for each situation of the survey, according to Gwet's agreement probability and the "multiclass Brier Score" for the FSV model (approach I). The vertical blue line indicates a random reference's Brier Score. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 148

7.8 Graph with each finishing situation according to the values of Gwet's agreement probability and the "multiclass Brier Score" of the FSV model (approach II). The vertical blue line indicates a Brier Score random reference . . . . . . . . . . . . . . . . . . . . . . . . . . 149

7.9 Player Location and how the distance to the goal influences scoring probability percentage 153

7.10 Player Location and how the angle to the goal influences scoring probability percentage . 154

7.11 Variation of the average values of the Voronoi areas of players who are with (BC) and without the ball (NB), in the inside zones (INS) of the "Effective Playing Space" (EPS) . . 155

7.12 Variation of the average values of the Voronoi areas of players who are with (BC) and without the ball (NB), in the Outside Frontal regions (OUT_F) of the "Effective Playing Space" (EPS) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 156

7.13 Variation of the average values of the Voronoi areas of players who are with (BC) and without the ball (NB), in the Outside Side regions (OUT_S) of the "Effective Playing Space" (EPS) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 157

7.14 Variation of the average values of the Voronoi areas of players who are with (BC) and without the ball (NB), in the Outside Side-Frontal regions (OUT_S_F) of the “Effective Playing Space” (EPS) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 158

7.15 Graph with the function of the natural logarithm (LN) that is introduced in the FSV model to capture the shape of the Voronoi cell, through the distance to the nearest opponent (DO). 159

7.16 Heatmap with the probability of scoring calculated by the ”Player Location” component of our FSV model (see 7.2.2) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 159

7.17 Heatmap with the probability of scoring calculated by the model of Pollard and colleagues (**Pollard2004**) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 160

7.18 Heatmap with the probability of scoring calculated by the ”zone” component of the model of Link and colleagues (**Link2016**) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 160

7.19 Exemplary graph of how the FSV of different players was compared. In this case, the probability that player A (black line) has a higher FSV than B (blue line) or C (red line) is given by the respective shaded zones. . . . . . . . . . . . . . . . . . . . . . . . . . . . . 161

7.20 Histogram with the values of the FSV of each player (A, B, C and D), when each coach chose ”E” as the ”best option” (continue to play, and not shoot or pass to shoot). . . . . . 161

7.21 Histogram with the frequency of the FSV of the ball carrier (player A), when each coach chose him as the ”best option” . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 162

7.22 Graph showing, for each situation of the survey, the comparison between the values of Gwet’s agreement probability and the ”multiclass Brier Score” that measures the accuracy of probabilistic predictions if the FSV model only have the ”Player Location” (distance and angle to the opponnent’s goal). The vertical blue line indicates a Brier Score random reference162

7.23 Graph showing, for each situation of the survey, the comparison between the values of Gwet’s agreement probability and the ”multiclass Brier Score” that measures the accuracy of probabilistic predictions with model proposed by Pollard and colleagues (**Pollard2004**). The vertical blue line indicates a Brier Score random reference . . . . . . . . . . . . . . . 163

7.24 Graph showing, for each situation of the survey, the comparison between the values of Gwet’s agreement probability and the ”multiclass Brier Score” that measures the accuracy of probabilistic predictions with the ”Zone” component of the ”Dangerousity” model proposed by Link and colleagues (**Link2016**). The vertical blue line indicates a Brier Score random reference . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 164

8.1 Sequence of the ball carrier decisions, through corresponding Voronoi diagrams . . . . . 178

8.2 Sequence of Voronoi diagrams illustrating the exploitation of the space behind the defensive line. *Note:* Illustration of the (inter)action between two players of the blue team, i.e., the ball carrier (number 11) and his teammate (a right back", with the number 4) . . . . . . . . . . . . . . . . . . 180

8.3 Start of a sequence of diagrams (A and B), illustrating an "in possession team" overall configuration and fDOF, during the first stage of an "effective possession episode". . . . . 182

8.4 End of a sequence of diagrams (C and D), illustrating an "in possession" team overall configuration and fDOF, during the conclusion of an "*effective* possession episode". . . . 184

8.5 Start of a sequence of diagrams (A and B), illustrating an "in possession" team overall configuration and fDOF, of an "*non-effective* possession episode". . . . . . . . . . . . . . 185

8.6 End of a sequence of diagrams (C and D), illustrating an "in possession" team overall configuration and fDOF, of an "non-effective possession episode". . . . . . . . . . . . . . 186

9.1 Start of a sequence of diagrams (A and B) of a collective high-press (by the blue team) . 194

9.2 Continuity of a sequence of diagrams (C and D) of a collective high-press (blue team) . . 195

9.3 Continuity of a sequence of diagrams (E and F) of a collective high-press (blue team) . . 196

9.4 End of a sequence of diagrams (G and H) of a collective high-press (blue team) . . . . . . 197

9.5 Variation of both teams SVA during the "possession episode" of Figures *Note:* The "Sum of Voronoi Areas" (SVA) time-series of the two teams, highlighting the instants of the diagrams illustrated in Figure 9.1 to 9.4, with a 3rd line (light blue) representing the partial SVA of the four players of the defensive line (two "side backs" and two "central backs") of the blue team. 9.1 to 9.4 . . . . . . . . . . . . . . . . . . . . . . 198

9.6 Sequence of diagrams (from A to F) illustrating the relevance of the "Voronoi area" as a metric to understand the tactical dilemma of a "central defender" . . . . . . . . . . . . . . 200

# List of Tables


4.1 Mean, first and last time-series $CH$ and $SVA$ values for the possession episodes with (In possession) or without ball (Out of possession) . . . . . . . . . . . . . . . . . . . . . . . . 83

4.2 Mean, first and last time-series $CH$ and $SVA$ values for non effective ($Np$) and effective ($Ep$) ball possession episodes. *Note: $t$-test $p$ values refer to $Np$, $Ep$ pairs.* . . . . . . . . . . 84

4.3 $ApEn$ of Convex Hull ($CH$) and Sum of Voronoi Areas ($SVA$) time-series, non effective ($Np$) and effective ($Ep$). *Note: $t$-test $p$ values refer to $Np$, $Ep$ pairs.* . . . . . . . . . . . . . . 84

6.1 Player's role in 4-2-3-1 and 3-4-1-2 team formations. . . . . . . . . . . . . . . . . . . . . . . 118

7.1 Ball Carrier's *Expected Voronoi Area* (VAe) in function of the *distance* to the centre of opponent's goal line (x) for each *region* of the Effective Playing Space (EPS) . . . . . . . 142

7.2 Teammates' of the ball carrier without the ball *Expected Voronoi Area* (VAe) in function of the *distance* to the centre of opponent's goal line (x) for each *region* of the Effective Playing Space (EPS) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 143

7.3 The table presents the results of the number of coaches that choose each possibility (A,B,C,D or E), in each one of the 50 finishing situations of the survey answered by the "Panel of Experts" (PE choices). The agreement between the coaches of the PE is calculated by the Gwet's AC1. In the following columns is showed the results of the "Finishing Space Value" (FSV) for each player in each situation (A, B, C and D). Finally, the last two columns present the Brier Scores that compare the probability of choosing one given "best option" (A, B, C, D or E) in the two approaches: by the subjective answers of a coaches' "panel of experts" (PE) and by the two versions of the Finishing Space Value (FSV) quantification model. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 165

7.4 The table specifies the results of the probabilities of the Finishing Space Value (FSV) quantification model (version I and II) to choose one ”best option” in each finishing situation. In each FSV model (I and II), the last column presents the Brier Score (BS), when these probabilities were compared with the probabilities calculated from the coaches’ ”Panel of Experts” (PE) subjective answers. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 166

7.5 The table presents the results of the probabilities of a quantification model that only includes the ”Player Location” (distance and angle to the opponent’s goal) to choose one ”best option” in each finishing situation. The last column presents the Brier Score of this model (BS PL), when these probabilities were compared with the probabilities calculated from the coaches’ ”Panel of Experts” (PE) subjective answers. . . . . . . . . . . . . . . . . . . . . . 167

7.6 The table specifies the results of the probabilities of the quantification models already presented by Pollard and colleagues (**Pollard2004**) and Link and colleagues (**Link2016**) (in this case, only to its component ”Zone”). The last column of each model presents the Brier Score (BS), when these probabilities were compared with the probabilities calculated from the coaches’ ”Panel of Experts” (PE) subjective answers. . . . . . . . . . . . . . . . . 168

# Introduction and theoretical essays

# Chapter 1

# General Introduction

## 1.1 Introduction

This thesis aims to investigate the performance of high-level football teams by analyzing players' interactions in the context of the game. We rely on the idea that the most general expression of a team's performance, i.e., its results (e.g. winning a game), cannot be linearly explained by the sum of the (micro) performance of each of its players (e.g., the distance covered by a player or their number of successful passes). In fact, time-motion analysis showed that football players' individual physical performances cannot be directly linked to team success (determined by league ranking), nor a discriminator of players' ability to perform at the highest level (Carling, 2013).

On the other hand, individual performances proved to be dependent on teams' tactical constraints (e.g., players' roles or positions in a team formation) (Altmann et al., 2021) and the quality of opponent teams (Lago et al., 2010). This complex reality took us to adopt an ecological dynamics framework (Duarte Araújo, Keith Davids, and Hristovski, 2006) to understand a football team's performance (D. Araújo and K. Davids, 2016), in line with the "synergism hypothesis" (Corning, 1983) and the "Holistic Darwinism", that situates *cooperation* as the main cause of evolutionary continuity and change (Corning, 2010). Thus, we defend in this thesis the idea that a team's performance emerges from a complex net of interactions between players on the pitch (teammates and opponents), which result in *functional effects* that are only achieved through these same interactions (synergies).

We argue that due to the *neutral* value of the concept of synergy in a broad sense (Corning, 2010; Corning, 2018), the study of the behavioural patterns that emerge from these synergies, revealing their properties, will lead to a better understanding of the performance of football teams. Regardless of whether the "payoffs" resulting from player interactions are positive, negative or neutral (Corning, 2010). Being a zero-sum game (Hirotsu et al., 2009), the typically opposing objectives of the two football teams means that the *functional effects* of the cooperation between a group of players of one of the teams, can be annulled (but also amplified) by the cooperation between players of the opponent team.

Thus, this thesis aims to contribute to understand the *functional synergies* of football teams, emerging from players' interactions when they want to perform a specific task (e.g., keeping possession of the ball, or making/avoiding a goal). It is certain that, due to the chaotic dynamics of the football game (Keith Davids, Duarte Araújo, and Shuttleworth, 2005; Mateus, 2005), the way that a group of players solves together a given game parcel cannot also linearly explain the (macro) result of a match. But it is no less true that a match's final result depends on the ability of teams to perform these collective tasks (Duarte et al., 2013; Vilar et al., 2013). Thus, the (meso) scale that focuses on the *interactions* between the team members and their synergies in solving a given game task, is for us the *ecological* scale on which coaches and researchers should focus (Keith Davids and Duarte Araújo, 2010).

This scale implies a *glocal* perspective to match analysis and training processes (Robertson, 1995; Caldeira, 2013), understanding the two-way influence (Ribeiro et al., 2019) between the *global* (the team) and the *local* interpersonal interactions (e.g., a pass between two players). However, a *glocal* perspective on a football team's performance led us to see how *reductionist* can be some quantitative approaches (e.g., based on players' dyads), but also how too *holistic* can be some others (e.g., studying team's centroids). In this context, we were interested in the methods that allow understanding how the *global* play space is divided by players during their interactions, using the (*local*) sense of the proximity between each player and their ”neighbours”. This justifies our idea that the synergies that emerge from football players’ interactions, can be *glocally* analysed from a spatio-temporal perspective through ”Delaunay triangulations” and the consequent ”Voronoi diagrams” (VD), to capture player’s ”space dominance” (Taki and Hasegawa, 2000; Efthimiou, 2021).

Therefore, in this thesis, supported in the *ecological dynamics* theoretical framework, we aim to test the ”synergism hypothesis” (Corning, 1983) establishing possible links between a football team’s performance and the functional effects emerging from players’ interactions. In this realm, from a spatio-temporal perspective, we argue that the players’ ”space dominance” potential perception are *affordances* that guide players’ interactions and their synergies. For this purpose, we will use VD and compound metrics to analyse players’ interactions and how their ”space dominance” is linked to collective performance in different scales of football high-level match environments.

## 1.2 Outline of the present thesis

This thesis is structured into three parts and ten chapters, which we briefly describe here.

### 1.2.1 General Introduction

In this first chapter, our purpose is to briefly frame our thesis that a football team’s performance is dependent on their players’ cooperative behaviour (synergies). The two following chapters are dedicated to review the *state of the art* around:

a) How the *synergism hypothesis*, aligned with an *ecological dynamics* perspective, can underpin the research of high-level football teams’ performance (chapter 2).

b) The usefulness of Voronoi-diagrams-based metrics to assess players’ interactive behavioural spatial patterns (chapter 3).

Based on these conceptual chapters (2 and 3), in the following chapters (4, 5, 6 and 7), we explore real high-level football matches positional data to capture different behavioural patterns that express players’ interactions. These patterns are essentially extracted from *Voronoi diagrams* (VD) compound metrics, that have the ability to assess players’ ”space dominance”. From our perspective, VD can allow the quantification of players’ potentially perceived *affordances* (Gold, 1995) and emerging players’ cooperative interactions. We argue that if a team’s synergies underpin its performance, then it will be possible to establish a link between performance parameters in some specific group task (e.g., maintaining the ball possession) and the *functional effects* emerging from players’ interactions in a given competitive environment (Keith Davids and Duarte Araújo, 2010).

Finally, the last three chapters (8, 9 and 10) are dedicated to a reflection on possible applications of this thesis from a coach’s perspective (chapters 8 and 9) and to a general discussion about how our theoretical work and the results of our applied studies can contribute to understand football team's performance (chapter 10). Suggestions for future research and a summary of this thesis's practical implications are also addressed in the last chapter 10.

### 1.2.2 How the synergism hypothesis, aligned with an ecological dynamics' perspective, can underpin the research of high-level football teams' performance

In the chapter 2, we defend the idea that a football team's performance can be analysed through the theoretical support of the *ecological dynamics* framework (Gibson, 1979; Keith Davids, Duarte Araújo, and Shuttleworth, 2005; Duarte Araújo, Keith Davids, and Hristovski, 2006) and the *synergism hypothesis* to life's evolution (Corning, 1983; Corning, 2010; Corning, 2018). Supported in a literature review, we begin by considering that football players can never *act* isolated from the match environment (Keith Davids and Duarte Araújo, 2010). As supported by Pol and colleagues (2020), teams can be conceptualized as dynamic complex systems interacting non-linearly with the environment (i.e., co-adaptively), and consequently, the work of each player can hardly be analysed outside the whole that is the team playing in a given match environment. For this reason, players always *interact* (with other teammates and opponents) in the match *dynamic* environment. In this realm, narrower definitions of *synergy* cannot be applied to team sports like football.

Based on a broad definition of "synergy", the *synergism hypothesis* supports the research around the "functional effects" that emerge from the interaction of the players of a given team, considering the competitive context. We defend here that team's performance is the result of the combined "*functional effects that are jointly created and that are not otherwise attainable*" by players individually (Corning, 2018).

In this context, the *functional effects* arising from players' interactions are a consequence of the team's synergies, which properties measurement provide very useful feedback information for coaches and other practitioners (D. Araújo and K. Davids, 2016).

In the second part of the chapter 2, we briefly review of the quantitative assessment methods already presented in the literature to assess players' interactions and team synergies. Is important to underline that the synergism hypothesis attributes equal importance to the *parts* and *wholes*, defending that the methods and metrics to study synergies should assume the challenge of reconciling *reductionist* and *holistic* approaches. From a spatio-temporal perspective, this challenge means that the metrics should aim to capture the *local* players' interactions (e.g., around the ball carrier) without losing the perspective of the *global* pitch landscape. Reviewing the methods that have this *glocal* potential, we demonstrate how Voronoi diagrams (VD) compound metrics can be a good solution to assess players' interactions by their *space dominance* patterns. From our perspective, VD can capture the patterns emerging from players' interactions (from their "joint work") and the properties of these synergies and resulting performances (payoffs). For example, to understand how teams achieve to dominate the game space, the team's collective ability to maintain the ball possession or the decision about the player in the best place to shoot.

### 1.2.3 Using Voronoi diagrams to assess high-performance football team synergies

In chapter 3, the discussion is around the quantification of the synergies' properties in the football match context and how the Voronoi diagrams-based methods can be useful in that quest. Being possible to measure the distances and angles between all players in the match, more complex measures can reconcile the *reductionist* and *holistic* approaches to study a football team's performance. In fact, positional data can extract the players' neighbour relationships through *Delauney triangulations* and consequently compute *Voronoi diagrams* (Chiu and Barnes, 2003). Voronoi diagrams (VD) allow the assessment of the "unique limiting convex polygon such that all points within a point's polygon are closer to this point than all the other points" (Kim, 2004, p233). In a VD, a Voronoi cell of a given player corresponds to the game space around that player and can be interpreted as his/her main "sphere of influence" or "dominance space"(Taki and Hasegawa, 2000).

From our point of view, these players' *dominance spaces* can be used to understand players' eventual perception of the spatial *affordances* (possibilities for action) in the game landscapes. Underpinned by an *ecological dynamics* theoretical framework (Duarte Araújo, Keith Davids, and Hristovski, 2006), we consider that the perception of these affordances constrains players' decisions and how they interact with the environment (e.g., teammates and opponent players). In a nutshell, spatial affordances constrain the emergence of team synergies, both on a local (e.g., around the ball carrier) or global scale.

In fact, in a football game, understood as a dynamic system (Keith Davids, Duarte Araújo, and Shuttleworth, 2005), not only at a given moment does the perception of the spaces around players depend on the position of all elements on the field, but also, circularly, this perception will influence the displacement options of each of the players individually in the next instant. Consequently, pitch space analysis from a *glocal* perspective (Robertson, 1995) can reveal patterns that emerge from the "collective work" (synergies) of a team pursuing some purpose (function).

Due to the *circular causality* (Pol et al., 2020), from these team synergies will emerge new spatial configurations that will result in new affordances to explore and, consequently, renewed synergies (Plumert and Kearney, 2018). We argue therefore that important synergies' properties, emerging from players' interactions, can be extracted from real matches positional data. In this case, to test if players' *dominance spaces* can be linked with a set of collective functions that are related to teams' performance (e.g., creating scoring opportunities, maintaining ball possession or achieving a certain territorial dominance). Using this conceptual approach, *Voronoi diagrams* were elected as the basic tool for quantifying synergies' properties in this thesis. The main idea behind this is that by assessing the distribution of the space by all the players that are on the pitch at a given time, it will be possible to capture teams' synergies' properties (dimensional compression, reciprocal compensation, interpersonal linkages and degeneracy) (D. Araújo and K. Davids, 2016). Even if some metrics allow the identification of different properties arising simultaneously from a football team's synergy, in this thesis we focus especially on each of these in four different studies that aim to test their relevance for the team's performance.

### 1.2.4 Team's global quest for territorial dominance

As an invasion "team game" (P. D. Memmert, 2012; Gudmundsson and Horton, 2017), football is essentially a human social confrontation between two groups, where the winning team is the one who scores more goals than the opponent (UEFA, 2009). This implies that players need to coordinate their actions within their team to take the ball close enough to the opponent's goal in order to score but prevent the opponent to approach their own goal. This reality lead Thorpe and colleagues to define the game as "a struggle for territorial dominance within a set of rules [...] decided by a system of scoring which symbolises the extent of victory" (Thorpe, Bunker, and Almond, 1986, p73).

Beginning with the question about what should mean a global collective *territorial dominance* of the playing field and how it can be measured, in chapter 4 we intend to investigate the relevance of this dominance for one team to overcome the opponent. In fact, if it can be proved the link between territorial dominance and the creation of scoring situations, then we could empirically reinforce the above-mentioned opinion of Thorpe and colleagues on the importance of a *territorial dominance*. To this end, in the applied study of chapter 4, we measured the ball possession *effectiveness* (Ueda, Masaaki, and Hiroyuki, 2014), observing the differences in the *territorial dominance* between the "possession episodes" that were able to approach the creation of score situations and all the others.

### 1.2.5 Passing affordances are constrained by players' distribution on the field, i.e., by the team's functional degrees of freedom

In chapter 5 we develop a novel approach, based on the *affordances* ecological perspective, to assess the configuration of passing opportunities that a team can achieve from their players' interactions (synergies). It is a methodological *proof of concept* based on the idea that a pass is not an exclusive decision of the ball carrier. It is a collective decision that emerges in a given moment from the affordances to pass appearing in the match and resulting from players' distribution on the pitch. This distribution crystallizes an instantaneous team configuration that constrains the opportunities to pass (passing affordances). For example, if a player is off-side or if two players are too close to each other, the opportunities for the ball carrier to pass the ball to another teammate will be globally reduced.

Thus, passing affordances can be captured as the team's *functional degrees of freedom* (fDOF), allowing its quantification. Players should coordinate their displacements, reciprocally compensating the movements of their teammates, to adjust the team's fDOF to their tactical purposes (e.g., maintain the ball possession). Consequently, the question of how to capture these fDOF in the dynamic of a football match is central in this chapter 5.

### 1.2.6 The specific contribution of each player to dominate the playing pitch

The "combination" or "division of labour" is a special type of synergy in the synergism hypothesis theoretical frame (Corning, 2003; Corning, 2010). It is equivalent to the "interpersonal linkages" property in the team sports synergies approach, i.e., "the specific contribution of each element to a group task" (D. Araújo and

K. Davids, 2016, p8). In team sports like football, it is crucial to assess this “specific contribution” of each player as a first step to understand team synergies. In chapter 6, our contribution is to understand how collective constraints impact the specific contribution of each player to their teams’ struggle for territorial dominance of the playing pitch. Thus, we investigate how the players’ roles (Goes et al., 2020) in a given team formation (D. Memmert et al., 2019) constrains players’ ”*space dominance*” emerging from the interactions in a given match environment.

### 1.2.7 Understanding players’ shooting degenerate decision-making

The last applied study of this thesis is a contribution to understanding players’ decisions in the realm of the most decisive event to match final results: *shooting decision-making* (see chapter 7). It is a very important functional effect resulting from players’ “joint work”, and this decision should not be seen as exclusive to the ball carrier. Although it is the ball carrier who will ultimately decide if it is more appropriate to shoot or pass, this is a decision that emerges from players’ interactions regarding the teams’ common scoring purpose and can therefore be seen as *collective*. For this reason, players’ degenerate decisions are based on their perception of match affordances.

In fact, the degeneracy as a property of team synergies (D. Araújo and K. Davids, 2016) where different elements can perform the same function (Edelman and Gally, 2001), is ubiquitous in living things and an important support to understanding all types of synergies (Kelso, 2022). In this case, in football finishing situations, players’ degenerate choices emerge from match environments. Thus, we argue that a model based on players’ perception of spatial affordances (“Finishing Space Value” or FSV) can be a possible way to understand players’ interactions and the emergent ball carrier’s tactical decisions. The FSV is a model based on two main players’ operational questions: a) is the opponent’s target successfully *reachable* from this point where I am (or where a given teammate is)? and, b) can I (or any teammate) shoot with *enough* space (low adversaries’ interference)?

Therefore, chapter 7 aims to establish a link between the ball carrier’s possible decision about who should shoot, and the spatial *affordances* of the game landscape where players are immersed (Gómez-Jordana et al., 2019).

### 1.2.8 A possible coach’s perspective on the performance analysis of the in-possession football team supported by Voronoi diagrams

Chapter 8 is dedicated to a reflection on the possible practical use, from a football coach’s perspective, of the applied research of this thesis. In these examples, the team *in possession* of the ball is the focus, situating analysis at three different levels: a) the ball carrier; b) the teammates of the ball carrier; and c) the overall team functional degrees of freedom configuration. Trying to demonstrate the possible use of this thesis concepts and tools in a coach’s tactical game analysis, our purpose is to bridge the gap between the investigation and practice.

### 1.2.9 Performance analysis of the out-of-possession football team supported by Voronoi diagrams

Chapter 9 presents two more practical examples of the possible use at the level of ”match performance analysis” through spatial quantifications based on Voronoi diagrams. In these examples, the team *out of possession* is the focus of the coach’s perspective, even if situating the scale of analysis at two different levels: a) the whole team coordination in a high-press situation; and b) the individual local decision of a first defensive line member.

In an essentially practical tactical reflection, the examples are presented as a way to establish a link between the coach’s point of view and what the applied research of this thesis could add to his/her activity and knowledge, through the positional data extracted from players tracking processes.

### 1.2.10 General discussion

The general discussion of chapter 10 summarizes the main thesis, presenting its limitations, conclusions, practical applications, and clues for future research. We underline here the relevance of understanding football teams’ performance as imminently situated in a performer-environment ecological scale (Keith Davids and Duarte Araújo, 2010), and why it makes little sense to overvalue individual actions, as (vice-versa) isolated holistic measures that fail short to explain the performance of football teams.

Thus, we conclude by discussing how the “synergism hypothesis” (Corning, 2018) can be effectively tested using the ”space dominance” patterns emerging from players’ interactions, and why these functional synergies are decisive to understand a football team’s performance.

## References


Altmann, Stefan et al. (2021). "Match-related physical performance in professional soccer: Position or player specific ?" In: *PLoS ONE* 16.9, pp. 22–24. DOI: doi.org/10.1371/journal.pone.0256695Editor:.

Araújo, D. and K. Davids (2016). "Team synergies in sport: Theory and measures". In: *Frontiers in Psychology* 7.SEP, pp. 1–13. DOI: 10.3389/fpsyg.2016.01449Team.

Araújo, Duarte, Keith Davids, and Robert Hristovski (2006). "The ecological dynamics of decision making in sport". In: *Psychology of Sport and Exercise* 7.6, pp. 653–676. DOI: 10.1016/j.psychsport.2006.07.002.

Caldeira, Nelson (2013). *Futebol glocal*. Funchal, Portugal: Sports Science, lda.

Carling, Christopher (2013). "Interpreting physical performance in professional soccer match-play: Should we be more pragmatic in our approach?" In: *Sports Medicine* 43.8, pp. 655–663. DOI: 10.1007/s40279-013-0055-8.

Chiu, Loren Z.F. and Jacque L. Barnes (2003). "The Fitness-Fatigue Model Revisited: Implications for Planning Short- and Long-Term Training". In: *Strength and Conditioning Journal* 25.6, pp. 42–51. DOI: 10.1519/1533-4295(2003)025<0042:tfmrif>2.0.co;2.

Corning, Peter (1983). *The Synergism Hypothesis: A Theory of Progressive Evolution*. McGraw-Hill, New York.

— (2003). *Nature's magic: Synergy in evolution and the fate of humankind*. Cambridge University Press.

— (2010). *Holistic Darwinism*. University of Chicago Press.

— (2018). *Synergistic Selection: How Cooperation Has Shaped Evolution And The Rise Of Humankind*. WORLD SCIENTIFIC PUBLISHING CO PTE LTD.

Davids, Keith and Duarte Araújo (2010). "The concept of 'Organismic Asymmetry' in sport science". In: *Journal of Science and Medicine in Sport* 13.6, pp. 633–640. DOI: 10.1016/j.jsams.2010.05.002.

Davids, Keith, Duarte Araújo, and Rick Shuttleworth (2005). "Applications of Dynamical Systems Theory to Football". In: *Science and Football V: The Proceedings of the Fifth World Congress on Science and Football* i, pp. 537–550.

Duarte, Ricardo et al. (2013). "The influence of manipulating the defensive playing method on collective synchrony of football teams". In: *Performance Analysis of Sport IX* 1, pp. 65–70. DOI: 10.4324/9780203080443.

Edelman, G. M. and J. A. Gally (2001). "Degeneracy and complexity in biological systems". In: *Proceedings of the National Academy of Sciences of the United States of America* 98.24, pp. 13763–13768. DOI: 10.1073/pnas.231499798.

Efthimiou, Costas J. (2021). "The Voronoi Diagram in Soccer: a theoretical study to measure dominance space". In: *arXiv preprint arXiv:2107.05714.*, pp. 1–32. arXiv: 2107.05714.

Gibson, J. (1979). *The ecological approach to visual perception*. Boston: Houghton, Mifflin and Company.

Goes, F. R. et al. (2020). "Unlocking the potential of big data to support tactical performance analysis in professional soccer: A systematic review". In: *European Journal of Sport Science* 0.0, pp. 1–16. DOI: 10.1080/17461391.2020.1747552.

Gold, Christopher (1995). “Advantages of the Voronoi spatial model”. In: *Proceedings of Eurocarto XII*. Copenhagen, pp. 1–10.

Gómez-Jordana, Luis et al. (2019). “Landscapes of passing opportunities in Football – where they are and for how long are available ?” In: *Barça Sports Analytics Summit-2nd edition At: Camp Nou- Barcelona*. November, pp. 1–14.

Gudmundsson, Joachim and Michael Horton (2017). “Spatio-temporal analysis of team sports”. In: *ACM Computing Surveys* 50.2. DOI: 10.1145/3054132. arXiv: 1602.06994.

Hirotsu, Nobuyoshi et al. (2009). “Modeling Tactical Changes of Formation in Association Football as a Zero-Sum Game”. In: *Journal of Quantitative Analysis in Sports* 5.

Kelso, J. A.Scott (2022). “On the coordination dynamics of (animate) moving bodies”. In: *Journal of Physics: Complexity* 3.3, pp. 1–16. DOI: 10.1088/2632-072X/ac7caf.

Kim, S. (2004). “Voronoi Analysis of a Soccer Game”. In: *Nonlinear Analysis: Modelling and Control* 9.3, pp. 233–240.

Lago, Carlos et al. (2010). “The effects of situational variables on distance covered at various speeds in elite soccer”. In: *European Journal of Sport Science* 10.2, pp. 103–109. DOI: 10.1080/17461390903273994.

Mateus, J. (2005). “In pursuit of an ecological and fractal approach to soccer coaching”. In: *Science and Football V : The Proceedings of the Fifth World Congress on Science and Football,* pp. 561–573.

Memmert, Daniel et al. (2019). “A tactical comparison of the 4-2-3-1 and 3-5-2 formation in soccer: A theory-oriented, experimental approach based on positional data in an 11 vs. 11 game set-up”. In: *PLoS ONE* 14.1, pp. 1–12. DOI: 10.1371/journal.pone.0210191.

Memmert, Prof Daniel (2012). “Tactical Creativity in Invasion Games”. In.

Plumert, J. and J. Kearney (2018). “Timing is almost everything: How children perceive and act on dynamic affordances”. In: *Advances in child development and behavior* 55, pp. 173–204. DOI: 10.1016/j.neuron.2015.02.042.Neuromechanical.

Pol, Rafel et al. (2020). “Training or Synergizing? Complex Systems Principles Change the Understanding of Sport Processes”. In: *Sports Medicine - Open* 6.1. DOI: 10.1186/s40798-020-00256-9.

Ribeiro, João et al. (Oct. 2019). “Exploiting Bi-Directional Self-Organizing Tendencies in Team Sports: The Role of the Game Model and Tactical Principles of Play”. In: *Frontiers in Psychology* 10. DOI: 10.3389/fpsyg.2019.02213.

Robertson, R. (1995). “Glocalization: Time-space and homogeneity-heterogeneity”. In: *Global modernities* 2.1, pp. 25–44.

Taki, Tsuyoshi and Jun ichi Hasegawa (2000). “Visualization of dominant region in team games and its application to teamwork analysis”. In: *Proceedings of Computer Graphics International Conference, CGI*, pp. 227–235. DOI: 10.1109/cgi.2000.852338.

Thorpe, R., D. Bunker, and L. Almond (1986). *Rethinking games teaching*. Department of Physical Education and Sport Science. Loughborough : University of technology.

Ueda, Fumiya, Honda Masaaki, and Horino Hiroyuki (2014). “The Causal Relationship between Dominant Region and Offense- Defense Performance - Focusing on the Time of Ball Acquisition”. In: *Football Science* 11, pp. 1–17.

UEFA (2009). *Praxiswörterbuch Fußball - Trilingual dictionary (German-English-French)*. Langenscheidt.

Vilar, Luís et al. (2013). "Science of winning soccer: Emergent pattern-forming dynamics in association football". In: *Journal of Systems Science and Complexity* 26.1, pp. 73–84. DOI: 10.1007/s11424-013-2286-z.

# Chapter 2

# How the synergism hypothesis, aligned with an ecological dynamics' perspective, can underpin the research of high-level football teams' performance

Caldeira, N., Lopes, R.J. & Araújo, D.

## Abstract

In this chapter, we argue that a valid framework to understand football teams' performance can be supported by the ecological dynamics approach and the "synergism hypothesis" to life's evolution. In a vision grounded in Gibson's theory of affordances, we consider that football players do not simply individually *act*, but instead always *interact* (with other teammates and opponents) in the match dynamic environment. Consequently, narrower definitions of Synergies cannot be applied to team sports like football. Based on a broad definition of "synergy", this theoretical framework supports the research around the "functional effects" that emerge from the interaction of the elements of a given team, considering the competitive context. We defend here that team's performance is the result of the combined "functional effects that are jointly created and that are not otherwise attainable" by players individually.
Presenting a review of the methods already used to measure football teams' synergies, we argue that the big challenge to assessing players' interactions and functional synergies should be centred in the reconciliation between a *reductionist* and a *holistic* approach. From a spatio-temporal perspective, this challenge means that the used metrics aim to capture the *local* players' interactions (e.g., around the ball carrier) without losing the perspective of the *global* pitch landscape. The article concludes that only by deepening our knowledge about team synergies emerging from players' interactions, it will be possible to progress in understanding a football team's performance.



## 2.1 Keywords

Degeneracy, Players' Interaction, Reciprocal compensation, Tactical performance

## 2.2 Introduction

Every year, the "*Fédération Internationale de Football Association*" (FIFA) elects the best player in the world, amplifying what happens in more restricted ceremonies at the level of continents, countries, leagues, regions, etc. Suffering from different biases (Coupe, Gergaud, and Noury, 2017), these individual awards are decided by votes from coaches, journalists and players, who are naturally influenced by social issues (Morsinkhof, 2014). However, does it make sense to award individual performances in a team sport? And to what extent does individual performance determine overall team performance (Duch, Waitzman, and Nunes Amaral, 2010)?

Individual awards reflect the cultural tendency to understand teams' performance as the *sum* of the individual performances of their players (L. Bornn, D. Cervone, and J. Fernandez, 2018). This tendency has also influenced the history of football applied scientific analysis, essentially driven by a physiological and biomechanical approach, following identical models of the individual sports (Bishop, 2008). Consequently, clubs' sports sciences and performance departments give little attention to players' interdependences and teams' tactical behaviour (Garganta, 2009), being mainly oriented to maximize players' individual capacities (Keith Davids and Duarte Araújo, 2010), essentially from a physical condition point of view (Carling et al., 2008; Thorpe, 2011; Akenhead et al., 2013; Bangsbo, 2015). This reflects a sort of organismic asymmetry (Keith Davids and Duarte Araújo, 2010), i.e., an inherent bias for seeking explanations of human performance and behaviour based on internal mechanisms and referents (Keith Davids and Duarte Araújo, 2010). Nevertheless, the time-motion analysis showed that football players' individual physical performances cannot be directly linked to team success (determined by league ranking), nor a discriminator of players' ability to perform at the highest level (Carling, 2013). On the other hand, individual performances proved to be dependent on teams' tactical constraints (e.g., players' roles or positions in a team formation) (Altmann et al., 2021) and the quality of opponent teams (Lago-Peñas and Dellal, 2010), proving the need to "consider the performer–environment relationship as the relevant scale of analysis" (Keith Davids and Duarte Araújo, 2010, p633).

In this context, football's collective nature (Teodorescu, 1984) hamper an analysis based on the individual, implying a complex approach to the study of a team's performance (Paul, Bradley, and Nassis, 2015; Bradley and Ade, 2018), based in a dynamics systems theory (Keith Davids, Duarte Araújo, and Rick Shuttleworth, 2005). Such approach allows an understanding of teams' analysis and the consequent training process in light of the "apparent paradox" (Morin, 1999) of the relationship between parts (players) and whole (team). Precisely the one that Aristotle already advocated in his book "Metaphysics" when referring that "the whole is over and above its parts, and not just the sum of them all" (Mitchell, 2012, p171). The "synergism hypothesis" can be such a paradigm when aligned with an ecological approach to team performance.

## 2.3 An ecological dynamics approach to collective performance

Assuming the complexity of football, every analysis of the performance of a team need always to be socio and culturally contextualized, equating after the necessary balance between the *independence* of each player and the *interdependence* with teammates and opponents (Davis and Sumara, 2010; Reindal, 1999). Thus, the collective performance of a high-performance football team (e.g., one match result or the final rank position in a league) emerges from the complex interactions between their players and the constraints of the competitive environment (J. Gréhaigne, 1992). In fact, football is a special social environment where the action of a given player in a certain instant emerges from the *opportunities for action* (affordances) directly perceived in the match landscape (Gibson, 1979). This perspective of Gibson was followed by the vision of Reed (1996) that evolution gives rise to animals that are capable of taking advantage of the relatively persistent affordances in a given environment. In the context of team sports, these ideas were taken to imply that the more successful teams are composed of players who have learned together to perceive shared affordances in the performance competitive environment (Pedro Silva, Garganta, et al., 2013).

From this theoretical perspective, the performance of a team is supported by the coordinated effort of their members, i.e., by *team coordination* (Gorman, Amazeen, and Cooke, 2010)(D. Araújo, P. Silva, and J. Ramos, 2014). Team coordination depends on the collective *attunement* of their players to shared affordances (Pedro Silva, Garganta, et al., 2013), to synchronize (Duarte, Duarte Araújo, Correia, Keith Davids, et al., 2013) (Floris R. Goes, Brink, et al., 2020) their efforts in a sort of *superorganism* (Duarte, Duarte Araújo, Correia, and Keith Davids, 2012). For example, the same group of players competing together during several seasons proved that the stability and longevity of team relationships have a positive impact on performance (Montanari, Silvestri, and Gallo, 2008). Moreover, creating training environments that simulate the shared affordances perceived in the competition can enhance collective performance (Pedro Silva, 2014), allowing players to adjust individual actions to functionally adapt to those of other teammates and opponents (Fajen, M. A. Riley, and Michael T. Turvey, 2009). These are the premises of the representative training concept (Pinder et al., 2011). In this perspective, by training exercises that recreate the competition environment, coaches can improve the ability of their players to "work together", establishing synergies that increase team coordination based on their elements' shared affordances (Machado et al., 2016).

As highlighted by Araújo and Davids (2016), team synergies regard *action*, meaning that a synergy is a physical process that realizes a task goal (function) under the guidance of affordance-specific information (i.e., shared affordances that are predicated on perception). Consequently, players coordinated actions establishing *functional synergies* may be decisive for the collective performance and the survival of the "fittest" team (Pedro Passos, Duarte Araújo, and Keith Davids, 2016). This is a quest that depends on the team's overall performance (one match final outcome or the final ranking of a championship). This rationale, very significant for all football coaches, is coherent with the "holistic Darwinism" theory and his previously proposed "synergism hypothesis" about the functional basis for the evolution of complex systems, in nature and human societies alike (Corning, 1983). For Corning, synergies are everywhere and

being ubiquitous the term “synergy” could be utilized as a “pan-disciplinary lingua franca for the functional effects produced by cooperative phenomena of various kinds” (Corning, 1998, p133).
In this line, using Corning (Corning, 2018) broad definition of synergy, in this chapter, we defend the idea that aligned with the framework of the ecological dynamics, the “synergism hypothesis” is able to underpin the research on football team’s performance.

## 2.4 The “synergism hypothesis” and the football performance

In the vision of Corning, evolution is considered a “multilevel process, from genes to ecosystems, and that interdependent coevolution is a ubiquitous phenomenon in nature” (Corning, 2008, p.22). This theory, opposing reductionist approaches, situates *cooperation* as the main evolutionary impulse of nature, assuming the complexity to understand the *functional effects* emerging from elements in interaction. Moreover, to underpin the research in different fields of knowledge is essential to recognize the “*functional relationships* among the units at various levels of biological organizations, from genomes to ecosystems, and on their consequences for differential survival and reproduction” (Corning, 2010, p21), assessing synergies. It will be no different to study interpersonal (players) coordination (J. S. Kelso, 2017) and the collective performance of high-level football teams (D. Araújo and K. Davids, 2016; Pedro Silva, Vilar, et al., 2016). However, is important to first clarify the concept of synergy assumed by the “synergism hypothesis” and its divergences from the meaning usually assumed in human movement science.

### 2.4.1 The concept of synergies in the human movement science

We should start to clarify that, in the “synergism hypothesis” (Corning, 2018), the scope of the concept of “Synergy” is not congruent with other meanings used in human movement science, implying the inevitable need to define it properly. This is a consequence of “different understandings of what “work together” may mean” (Mark Latash and Zatsiorsky, 2015, p205), leading to the current reality of ”one term, many meanings” (Bruton and O’Dwyer, 2018, p2762). Is important to stress that, in the field of the human movement sciences, the concept of “Synergy” was strongly influenced by the pioneer works of Bernstein (1967) around human coordination and motor control. According to Latash (2021, p3), the level of synergies as conceptualized by Bernstein serves two main functions: (1) organizing numerous elements into groups; and (2) ensuring the dynamical stability of movements. From the first function emerged the importance of synergies as a way to manage systems with a large number of “redundant” degrees of freedom, and the second function underlined their role in ensuring the dynamical stability of actions (Mark L. Latash, 2021).
Trying to redefine a new theory of motor synergies, Latash and colleagues (2007) gradually reformulate Bernstein’s concept of synergies. Namely redefining the problem of motor redundancy, as the “principle of abundance” (Gelfand and M. L. Latash, 1998), and accentuating the importance of variability in both neural and motor processes to postulate that the brain facilitates ”good enough” solutions (Mark L. Latash, 2021). For Latash, synergies played an assumed role in ensuring the dynamical stability of actions, a

property captured by the "uncontrolled manifold" (UCM) approach (J. P. Scholz and Gregor Schöner, 1999; J. Scholz and G. Schöner, 2014). Underpinning the UCM approach, Latash (2008) defined synergy as having necessarily three conditions: a) *sharing* (the elements should all contribute to a particular task); b) *error compensation* (the flexibility/stability feature of co-variation among elemental variables); and c) *task-dependence* (the ability to a set of elements to form a different synergy with a different purpose). These conditions classify a certain interaction of elements as being a synergy or not (a non-synergy), depending on whether it is possible to measure in a certain system behaviour these three conditions or not. In this line, the UCM approach was a quantification method that already supported not only investigating the motor control domain (Papi, Rowe, and Pomeroy, 2015; Vaz et al., 2019) and interpersonal synergies (Slomka et al., 2015). However, the challenge to investigate synergies within the scope of sports teams fail short if is only oriented to conclude when will a synergy exist or not (for example, using the UCM approach). Instead, we argue that it should aim to assume the more wide challenge of capturing the *functional effects* that emerge from players' interactions, as proposed by Corning in his "Synergism Hypothesis" (Corning, 1983).

### 2.4.2 A broad concept of synergies to understand football performance

In the theoretical framework of the "synergism hypothesis", "synergies are everywhere" (Strong and Phillips, 2001, p130) because "it appears that no single part of the Universe can predict the behaviour of the whole" (Fuller, 1982, p69). Congruently, thinking in the functional effects produced by a football team, it is really difficult to say in a given moment that an element (player) is acting completely disconnected from its whole (team), as players' interactions are implicit to the game's dynamic J. Gréhaigne, 1992. At least in the high-performance context, no player's actions can be disconnected from the actions of his/her teammates and/or opponents, being acceptable the maxim that "in football, there are no actions but interactions" (Lobo, 2019).

In this line, as supported by Pol and colleagues (2020), teams can be conceptualized as dynamic complex systems interacting non-linearly with the environment (i.e., co-adaptively). Consequently, the work of each player can hardly be analysed outside the whole that is the team or, at least, a sub-sphere of it (i.e., a team sub-group). This implies that to study the dynamics of a football team during a match, we should move away from narrower definitions of what synergies can be (as used in other contexts) and move closer to a concept of synergy in a broad sense, as the combined "*functional effects that are jointly created and that are not otherwise attainable*" (Corning, 2018, ch2). A preliminary point about the concept of the synergy of Corning (Corning, 2018) is that it is "value-neutral". In fact, for him, the term "synergy" refers to *combined effects* of all kinds depending on the context, including *eufunctional* (positive synergy), *dysfunctional* (negative synergy), or even *neutral*. Synergy may be viewed positively from the perspective of the predators but rather negatively from the point of view of their prey (Corning, 2018). Equally, in team sports, a combination of three teammates to overcome the opposition of two adversaries has different *functional effects* values depending on the considered team Bruno Travassos, Duarte Araújo, et al., 2012. Consequently, as team sports are usually "zero-sum" games (Hirotsu et al., 2009), in competitive match environments it will always be possible to identify positive or negative synergies in a given match situation (depending on the team's perspective). In its theoretical "hypothesis about how Nature handles biological complexity" (S. Kelso, 2009, p1537), the ideas of Corning (1983) were grounded in some pivotal elements that are still current in the complexity theory applied to different areas (Morin, 2008; Mason, 2009; Balague et al., 2013; Koliba et al., 2022). Two of these "pivotal elements" are connected, being particularly significant to understand the football team's performance: 1) an interactional (multi-level and multi-factorial of causation); and 2) a hierarchical model of complex systems.

From the first element, is important to note that a "synergy perspective suggests a paradigm that explicitly focusses on both wholes and parts, and on the interactions that occur among the parts, between parts and wholes and between wholes at various "levels" of interaction and causation" (Corning, 2018, ch2). In fact, the *synergy paradigm* (Corning, 2008) attributes equal weight to both reductionist and holistic perspectives, defending the interdependence of downward and upward causation. This is evident in a football context, as teams' global behaviour influences individual performances, but also players' abilities influence the overall team performance capabilities. For example, teams' performance is a determinant of football players' individual market values (Richau et al., 2019), but circularly, teams formed by players with higher market values have better results (Matesanz et al., 2018). In other words, in a synergy paradigm "parts inherit their functions from the whole that they compose [in a] closed loop of entailment" (M. T. Turvey, 2007, p691), evidencing a "circular causality" (Marsh et al., 2006). This synergy feature is well synthesized by Turvey (2007, p691) when he stated that the "two defining characteristics of a synergy of Ck components are: (1) the role or function of any component Ci is dependent on the synergy and (2) the synergy's function F is dependent on the larger system of which Ci is a part".

The second "pivotal element" of Corning's "synergism hypothesis" is supported by a hierarchical model of complex systems that highlights a nested set of functional parts-wholes relationships (e.g., in a hierarchy of organelles, cells, tissues, organs, animals, societies, ecosystems, etc.). Respecting the synergies' circular causality, an organism's parts may establish functional priorities for the whole (e.g., the reproductive needs), but also the higher levels in the biological hierarchy may set priorities for lower levels (Corning, 2010). In sports performance, the coordination of a team "as a unit" is not only affected by global-local constraints but also by constraints emerging from the other sense, (i.e, local-global), forming real bi-directional self-organizing tendencies (Ribeiro et al., 2019). Giving an example of a football match situation, Santos and Passos underlines that "sometimes synergies may be formed between two defenders (dyadic level) and influence the soft-assembling of synergies of an entire defensive sector, whereas at other times this meso-level of the defensive sector may influence how synergies between two defenders will be formed" (Santos and Pedro Passos, 2021, p11). This is why a coaches' game model for a football match (Clemente and Rocha, 2013) can't preview a tactical plan fully defined in advance (P. Silva, 1995), because its implementation will only emerge from the ongoing interaction between the own team and the opponent (Garganta and J. F. Gréhaigne, 1999). Therefore, in this theoretical framework of the "synergism hypothesis", the functional effects of team synergies only can be ecologically verified in the competitive environment (D. Araújo and K. Davids, 2016), stressing the importance of the match analysis to model the constraints of training environments through a representative learning design. These ideas have already been developed by Pol and colleagues (Pol et al., 2020) in a concrete proposal of a training process (Synergizing) based on the constraints-led approach and in the properties of interdependence, nestedness, and circular causality.

## 2.5 The "synergism hypothesis" and the team sports' research

In this chapter, we argue that the broad definition of synergy and the "synergism hypothesis" of Corning (1983) to life's evolution, can support the research around the "functional effects" that emerge from the interaction of the elements of a given team, in the competitive context of a team sports' match like football. It is true that with the sense given by Corning, it will not be possible to distinguish a "synergy" from a "non-synergy" as with the rationale of Latash (2008). In fact, the idea that synergies only "occur when two or more variables co-vary to stabilize a performance goal" (Robalo et al., 2021) corresponds only to one type of the "functional effects" of Corning's definition. Namely, it refers to the property of "error compensation" mentioned by Latash (2008) about the flexibility/stability feature that is also referred to as *reciprocal compensation* (M. Riley et al., 2011). This property refers to the ability of one element of the synergy to react and adapt the system to changes in others, and although it was only recently operationalized in sports, it can be found in motor control with the UCM approach (Duarte Araújo, João Ramos, and R. Lopes, 2016). In team sports, this approach was also used by Passos and colleagues to investigate players' mutual dependency "achieved due to temporary compressions of d.f. [degrees of freedom] compensation which are the necessary features to the emergence of functional synergies" (P. Passos, Milho, and C. Button, 2018, p623).
The UCM, as a "control hypothesis about a selected performance variable whose value the system assumes to stabilize" (P. Passos, Milho, and C. Button, 2018, p622), was used to study players' interactions in Rugby (P. Passos, Milho, and C. Button, 2018), Badminton (P. Passos, Lacasa, et al., 2020), or a basketball dribble task (Robalo et al., 2021). However, as stressed by Kiefer and colleagues (Kiefer et al., 2017, p12) when they studied the coordination and coherence in pedestrian groups and tried to use the UCM method, the "reciprocal compensation may not be a general characteristic of all forms of interpersonal coordination in human groups". This is also the perspective of Riley and colleagues (M. Riley et al., 2011).
Accordingly, in the vision of Corning, synergies are a ubiquitous phenomenon in nature (and human societies), expressing much more properties than reciprocal compensation (Corning, 2010). Based on several examples from varied areas of knowledge, Corning presents a long list of different kinds of synergies that accentuates diverse properties (Corning, 2003), e.g, the "synergies of scale", "threshold effects" and "phase transitions", "functional complementarities", "combination and division of labour" or "information sharing". In reality, Corning's "synergism hypothesis" is "an economic theory of *cooperation* and *complexity* in evolution, whose key theoretical claim is that the *'payoffs'* produced by various kinds of synergy are responsible for the evolution of complexity" (Mysterud, 2004, p118). Consequently, the "synergism hypothesis" is linked to the concept of "functional group selection", where the "causes of synergistic selection, like those of natural selection, are always situation-specific" (Corning, 2010, p84). In other words, what really matters for Corning are the *payoffs* that result from the *combined functional*

*effects* of things “working together” (Corning, 2010), e.g., economies of scale, increased efficiencies, reduced costs, higher yields, lower mortality rates, etc.. This Corning’s perspective was influenced by John Maynard Smith (Smith, 1998), that, investigating evolutionary genetics, defined synergy as the non-additive payoff increment to cooperating “partners”. In team sports, the *payoff* (a final outcome or result), whether positive, negative or neutral, is usually known as “performance”.

In this realm, the studies centred on teams’ payoffs (performance) in the competitive environment are countless, e.g., team success (Lepschy, Wäsche, and Woll, 2018), goals (Pratas, Volossovitch, and Carita, 2018) or play outcomes (Mcinerney, 2017). Equally, teams’ overall results can be also analysed through parameters that supposedly support them, i.e., key performance indicators (Filetti et al., 2017; Brito Souza et al., 2019). However, Corning (2010) stressed that the investigation around synergies needs to establish a link between the performance (payoff) and the behaviour of the interacting elements (e.g, in two different environments). From the vast complexity-friendly methods (Koliba et al., 2022), Corning highlighted three methodologies to test the “synergism hypothesis”: 1) synergy minus one; 2); “cost vs benefits” in game theory models; and 3) comparison of the functional differences in system’s behaviour (Corning, 2010).

In the first type of study, Corning stresses the importance of comparing the performance of a group before and after removing or neutralizing just one of its elements (Thomas and Casebeer, 2004). These functional effects, assessed at different scales, can be exemplified in the football context by the resilience (or not) of a given team to the absence of a “star” or decisive player. In this vision, synergies will be so weaker in a team, the greater the reduction in its performance due to the absence of a single player (see an example of Real Madrid’s performance in Arvind, 2020. However, apart from more or less speculative statistics, the complexity of the game, with a great number of always-changing elements and environments (venues, opponents, etc.), hamper testing the football team’s synergies with this method.

In the second type of method, Corning emphasized the utility of the game theory to the study of synergies (Smith, 1998), because it deals in its roots with “players” making decisions that are interdependent (Wright, 2021). From this point of view, functional effects can be assessed in supposed cooperative human interactions (Procaccia, Shah, and Tucker, 2014). This can be exemplified when football players of the same team decided to not cooperate with their teammates (RMCSport, 2021), with consequences in team synergies that may be measured, e.g., by networking techniques (Duch, Waitzman, and Nunes Amaral, 2010).

Finally, the third type of method includes all studies that compare the behavioural patterns of the cooperative interaction of the elements of a system, with their respective functional effects (and possibly with the synergy’s payoffs). A vast typology of studies is exemplified by Corning (Corning, 2010)), including the comparison of behavioural patterns extracted from different cooperative environments (e.g., hunting, food sharing, helping, nesting or allomothering) with the correspondent functional effects and /or payoffs (e.g., colony-size or group-size effects, or a species survival rates).

In the sports field of investigation, these ideas are usually tested. This is clear, for example, in all studies that investigate the “Ringelmann effect” that negatively correlates the increasing size of a group with less productive individual behaviours (de la Fuente Vizcay and Sarmiento, 2020). This effect is related to social loafing, i.e., the phenomenon of a person exerting less effort to achieve a goal when they work in a group than when working alone (Heuzé and Brunel, 2003; Czyż et al., 2016; Polozov et al., 2019). Equally, in the team sports context, an important group of studies that are part of this third type of methods suggested by Corning to study synergies, are the comparative studies between the existence of persistent affordances in two different environments (e.g., competition and training). The importance of a training process that includes plenty of representative tasks (Duarte Araújo, Keith Davids, and Pedro Passos, 2005), is actually supported by the "synergism hypothesis" and the idea that it is the "*functional effect*s of various kinds (in a given environment) that determine the differential survival of the genes, and structures, and behaviours that are responsible" (Corning, 2010, p85). As mentioned before, this perspective is congruent with the idea that adaptation to *persistent affordances* is key in evolution (Reed, 1996). In fact, in a sports competition, the collective performance that decides the survival of the "fittest" team (Pedro Passos, Duarte Araújo, and Keith Davids, 2016) is a consequence of the *attunement* that a group of players can have to the shared affordances of that environment (D. Araújo, P. Silva, and J. Ramos, 2014).

Consequently, as sports teams prepare their adaptation to competitive environments in simulated training environments, is crucial to investigate the level of *representativeness* of the training tasks (Pinder et al., 2011; Santos, Duarte, et al., 2018). This can be done by comparing the persistent affordances (patterns) in both environments (McGuckian, Cole, and Pepping, 2018) and the functional effects that emerge from players' interactions (synergies). In a parallelism with the examples given by Corning about nature ecosystems (Corning, 2010), several studies already started to pave the way to understanding team synergies in sport (D. Araújo and K. Davids, 2016) and how training environments can better simulate the competitive ones (Pedro Passos, Duarte Araújo, and Keith Davids, 2016).

This was the case of the work about Futsal of Travassos and colleagues (Bruno Travassos, Duarte, et al., 2012), when they compared the speed and regularity of the ball (affordances) and the functional effects resulting from the players' interactions in competition, measuring the pass accuracy performance in four different training designs. In this good example of the synergies investigation in team sports, they conclude that "changes in task constraints such as increasing the number of possibilities for passing actions seemed to improve the representativeness of practice task design, in relation to the competitive performance environments in team sports" (Bruno Travassos, Duarte, et al., 2012, p1453). Silva and colleagues (Pedro Silva, Vilar, et al., 2016) were also able to establish a link between practice and the improvement of team synchronization speed (functional effect). In this case, by capturing the time delays in the players' co-positioning readjustments, they achieved to assess teams' synergies and players' reciprocal compensation (even without an evident link to performance payoffs).

Some other works contributed to increasing the knowledge of the affordances and the functional effects resulting from players' interactions in the training contexts, even not establishing a comparison with competitive environments. It was, for example, the studies about how the presence and distance of a defender influence the run-up velocity and accuracy of a football player crossing a ball (Orth et al., 2014), or how the numerical relations and skill level constrain co-adaptive behaviours in football small-sided and conditioned games (Pedro Silva, 2014). On the other hand, sports science investigation about players' interactions in competition registered amazing progress in the last decade, supported on the development of various technologies (Barris and Chris Button, 2008; Buchheit et al., 2014). These technologies allow an increasingly frequent use of positional data in team sports performance analysis (Gudmundsson and Horton, 2017; F. R. Goes et al., 2020), with several reviews of these studies having been published in recent years (Sarmento et al., 2014; Low, Coutinho, et al., 2020).

These studies were supported by metrics that capture players' interactions in a given spatio-temporal referential (e.g., a time-lapse of a match performed on a football pitch), approaching different properties of teams' synergies. However, the methods used to quantify the synergies between the members of a team have difficulty in simultaneously capturing the relationships between the parts without losing the global context of the teams or vice versa. In fact, the metrics used are either more *reductionist* or more *holistic*, hardly being both simultaneously.

## 2.6 Reductionist and holistic methods to investigate football team synergies

In this chapter, we defend the idea that a football team's performance is determined by much more than the simple *sum* of their players' individual performances. In fact, we agree with the vision that "due to the nestedness of constraints, there is no need to reduce the training unit to individual players in team sports or to a subsystem in individual sports" (Pol et al., 2020, p8)(Pol et al., 2020). A team's performance is a result of players' interactions, being critical in the assessment of these interactions (synergies).

Our perspective is that the synergy hypothesis can support the analysis of an interpersonal social reality (football team performance), in parallel with the vision of Kelso (2022)that it can solve four problems of complex biological systems. The first two (degeneracy and multifunctionality) are ubiquitous in living things and naturally in team sports synergies, expressing respectively how the same outcome can be achieved using coordinated combinations of very different components and how different outcomes can be achieved using the same components. The third and fourth relate to findings verified in the quantification of synergies. That is, how the relations among interacting components can be preserved despite changes in parameters and how to compress a state space of very many dimensions into a control space of just a few dimensions (dimensional compression). It was precisely based on these two last types of synergies' features, that Haken (1983) established the basis of the "*Synergetics*", an interdisciplinary science explaining the formation and self-organization of patterns and structures in open systems far from thermodynamic equilibrium. Through the lens of non-linear mathematical models such as the "HKB model" proposed by Haken and colleagues (1985), the Synergetics approach was able to understand how "the state (i.e., the synergy) of the originally high-dimensional system (i.e., the team) can be summarized by a few variables or even a single collective variable, the order parameter" (D. Araújo and K. Davids, 2016)[p7].

### 2.6.1 A "synergetics" reductionist approach to team sports synergies

As the principles of the "Synergetics" (Hermann Haken, 1983) were grounded in the degree of synchronization between two oscillators, the first natural way to investigate team sports synergies was based on the interactions of pairs (dyads). In this realm were used as parameters of order and control the distances (or angles) between players (teammates or opponents) or between players and objects (to the ball, target / basket / goal). This strategy proved to be "able to accurately describe different states of the dyadic system" (Pedro Passos, Duarte Araújo, and Keith Davids, 2013, p68) in several team sports (Pedro Passos, Duarte Araújo, Keith Davids, and Richard Shuttleworth, 2008; Cordovil et al., 2009; Pedro Passos, Duarte Araújo, Keith Davids, Gouveia, et al., 2009; J. E. Lopes et al., 2012; Caetano et al., 2019; Headrick et al., 2012). This was the case, for example, of Araujo and colleagues (D. Araújo, K. Davids, et al., 2003) that studied "1 v 1 situations" in team sports, with the interpersonal distance between the attacker and defender as a control parameter and the distance of both players to the goal area as the order parameter. Equally following the basis of the Synergetics (Hermann Haken, 1983), the calculation of the "relative phase" was performed also (through the Hilbert transformation) to study the interactions between tennis' players (Palut and Zanone, 2005). Detecting in-phase patterns with this methodology, it was possible to measure the dyadic interactions in the game of futsal (B. Travassos et al., 2011; Vilar et al., 2012) or the strong attractions within the attacking–defending basketball dyads in the longitudinal direction (Bourbousson, Sève, and McGarry, 2010). Some of these studies that presented a reductionist focus on the dynamics of players' dyads, had the merit to interpret the functional effects arising from these interactions, e.g., how fatigue influenced the degree of synchronization between football players in a "5vs5" small-sided game (Coutinho et al., 2018).

### 2.6.2 A holistic approach to team sports synergies based on the "Synergetics"

Despite all the relevance of the investigations around dyads, the natural step of team sports researchers was to "extend synchrony measures to groups larger than two people" (López-felip and Till D Frank, 2017, p706). This was the case of Duarte and colleagues (Duarte, Duarte Araújo, Correia, Keith Davids, et al., 2013, p558) who assess the "dynamics of team – team and player – team synchrony in professional association football" through the *Kuramoto* order parameter model (T. D. Frank and Richardson, 2010). As described in detail by Duarte and colleagues (Duarte, Duarte Araújo, Correia, Keith Davids, et al., 2013, p558-560), this method rests on the technique of cluster phase analysis and allows "the calculation of the mean and continuous group synchrony [...] as well as the individual's relative phase with the group measure", through the treatment of the "phase time-series obtained with Hilbert transform". In Corning's perspective of what is synergy (Corning, 2018), the degree of synchronization between players or teams does not elucidate *per se* the functional effects emerging from there or the collective performance (payoffs). Instead, it is necessary to establish a clear link between the behavioural patterns and the functional effects emerging from players' interactions.

This was achieved, for example, through studies that aimed to understand how the defensive playing methods (zone or man-to-man) constrain the collective synchrony of football players during a "Gk+5vs.5+Gk" small-sided game (Duarte, Bruno Travassos, et al., 2013) or to know the influence of the level of opposition, game phase and field zone in six matches of a team from the First Portuguese Soccer League (Pinto, 2014). Equally, it enabled the comparison between youth and professional team levels (Vaughan et al., 2017) and, more recently, to establish a link between the variations of synchronization and critical performance changes (functional effects as ball possession changes, goals scored, etc.) (Carrilho et al., 2020).

However, regardless of all its merits to understanding players' interactions, the Kuramoto model "is limited in that high synchrony can be a consequence of the players simply being very close to each other within that one-dimensional space (e.g., x-dimension), whereas, conversely if players are far apart within that dimension, synchrony would be low" (López-felip and Till D Frank, 2017, p707). Thus, even if the impact of the principles of the "Synergetics" (Hermann Haken, 1983) has been enormous throughout the science of human movement, other holistic methods not based on synchrony were proposed to investigate players' interactions in team sports. These methods were grounded in a broader definition of "synergies" (Corning, 2018) looking to capture different properties of team synergies (D. Araújo and K. Davids, 2016) with "holistic" methods that diverge from the "Synergetics". A good example of possible metrics to understand team sports was proposed by Schöllhorn (2003), in a set of *compound physical variables* that describes the behaviour of a team in space and time as a whole from a holistic perspective

### 2.6.3 Compound physical variables to holistically assess team sports synergies

Interpreting how the *coordination dynamics* ideas (S. Kelso, 2009) can be applied to team sports, Schöllhorn (2003) proposed a set of *compound physical variables* such as "a) time courses of movements of several or all players, b) covered area of several or all players, c) common centre of gravity of several or all team members d) geometric shape which is formed by several or all team members" (Schöllhorn, 2003, p44).

Some of these variables weren't exactly new (as the "centre of gravity", (J. F. Gréhaigne, Bouthier, and David, 1997), or were already known by other denominations (as the "effective play-space", (J.F. Gréhaigne, Mahut, and A. Fernandez, 2001). Although, accentuating this holistic perspective in the approach to "coordination dynamics", the work of Schöllhorn ((2003) had a great impact on team sports research. Examples of such compound positional variables that allow capturing "the time-evolution of a synergy" (D. Araújo and K. Davids, 2016, p7) of the all team behaviour by a single parameter (by dimensional compression), include: a) the geometrical centre of teams, i.e. "the mean (X,Y) of all players of one team", as said Frencken and Lemmink (2008, p163), usually known as "centroid", which represents a kind of *centre of mass* of a team. This "collective variable" was used in various sports (W. Frencken and K. Lemmink, 2008; Lames, Ertmer, and Walter, 2010), with a particular emphasis on football (Roger Bartlett et al., 2012; H. Folgado et al., 2012; Merlin et al., 2020). It was also used to assess the variability of inter-team distances associated with match events in elite-standard soccer (Wouter Frencken, Poel, et al., 2012), as part of a "data-driven model to measure pass effectiveness" (Floris R. Goes, Kempe, et al., 2019) or to study teams interactions in official "seven-a-side" youth football matches (Clemente, Couceiro, et al., 2014). With some variants, as the "weighted centroid" (Clemente, Couceiro, et al., 2014), or dividing its computation in "subgroup centroids" (F. R. Goes et al., 2020; B. V. Gonçalves et al., 2014) this variable was already largely used to understand players' interactions in training and /or competitive environments (Wouter Frencken, Koen Lemmink, et al., 2011; Duarte, Duarte Araújo, Correia, and Keith Davids, 2012; Sampaio et al., 2014; B. Gonçalves et al., 2016; Olthof, W. G. Frencken, and K. A. Lemmink, 2018; Hugo Folgado et al., 2019; Low, Boas, et al., 2018). A systematic review of this important compound variable was done by Morillo-Baro and colleagues (2020).

b) the team ranges (also known as length and width of the team), (Lames, Ertmer, and Walter, 2010), which represent the size of the team in the longitudinal and lateral field directions; and the combinations of these variables in the "length-per-width (LPW) ratio" (Pedro Silva, Duarte, et al., 2014; Olthof, W. G. Frencken, and K. A. Lemmink, 2018) was also used in several studies about the collective behaviour of football teams (H. Folgado et al., 2012; Barnabé et al., 2016; Low, Boas, et al., 2018).

c) the surface area occupied by teams was used by Frencken and Lemmink (2008) to complement the centroid metric due to its limitations to clarify the players' distribution on the field and can be defined as the total space covered by a team, referred to as the area within the *convex hull*(Wouter Frencken, Koen Lemmink, et al., 2011). As mentioned, this variable is identical to the effective play-space (EP-S) as proposed by Gréhaigne and colleagues 2001. This kind of quantitative approach (regardless of its specifics and denomination), was extensively used to study situations of "small sided games" in football (W. Frencken and K. Lemmink, 2008; Wouter Frencken, Koen Lemmink, et al., 2011; Duarte, Duarte Araújo, Correia, and Keith Davids, 2012; Pedro Silva, Duarte, et al., 2014; Barnabé et al., 2016; B. Gonçalves et al., 2016; Olthof, W. G. Frencken, and K. A. Lemmink, 2018), but also to evaluate "real match" team interactive behaviours (Roger Bartlett et al., 2012; Moura, Martins, et al., 2012; Floris R. Goes, Kempe, et al., 2019) or the effects of training processes in technical-tactical variables of performance (Aquino et al., 2016; Low, Boas, et al., 2018).

d) the stretch index of teams (Bourbousson, Sève, and McGarry, 2010), also denominated as "radius" by Yue and colleagues (2008), represents the mean dispersion value of the players around the centre of each team (i.e. the geometrical centre), and was used in some football studies (Roger Bartlett et al., 2012; Moura, Martins, et al., 2012; Barnabé et al., 2016; Coutinho et al., 2018; Olthof, W. G. Frencken, and K. A. Lemmink, 2018). In a variant of this parameter, some studies (Roger Bartlett et al., 2012; Moura, Martins, et al., 2012; Floris R. Goes, Kempe, et al., 2019) still use the "Frobenius norm", which can be defined as "the square root of the sums of the squares of the distances between all pairs of players ignoring the goalkeeper" (R. Bartlett, Wheat, and Robins, 2007, p400). The statistical treatment of these tactical variables using integer values or relative (as the distance "between team centroids", "centroid progression", distance "between team centroid and target", differences of "effective playing space", etc.), can include linear and non-linear methods like "the absolute values (mean), normalized approximate entropy (ApEn), and coefficient of variation (CV)" Merlin et al., 2020, p341.

However, can also aim to capture synchronization of the collective variables, for example, the "centroid" in the x and y axis, from the "offensive" and "defensive" teams (B. V. Gonçalves et al., 2014; Merlin et al., 2020). An extensive review of these compound tactical variables, which have been gaining increasing expression with the technological advances that have allowed the collection of positional data with ever greater detail and precision, and all the statistical methods used to treat them, can be found in the works of (Clemente, Duarte Araújo, and Keith Davids, 2017; F. R. Goes et al., 2020; Low, Coutinho, et al., 2020; Rico-González et al., 2020).

## 2.7 Present and future challenges to test the "synergism hypothesis" in football

Grounded in a broad concept of synergy, the "synergism hypothesis" (Corning, 2008) attributes equal weight to both *reductionist* and *holistic* perspectives, highlighting the need to capture the *circular causality* (M. T. Turvey, 2007) between parts (players) and wholes (teams). However, it is a huge challenge to assess, for example, the local interactions between two players without losing his/her context on the global match landscape.

In this realm, some important advances were recently achieved, as the authors propose methods that reconcile a global holistic analysis with the narrower view that is inevitable when we intend to detail local interactions. For example, based on the player-ball-goal angle (PBGA), Carrilho and colleagues (Carrilho et al., 2020) proposed to capture the degeneracy of the teams through the changes in the players' distribution by different team configuration codes. By the "convex hull of the subgroups" (each bin defined by a measure of π/3 of the PBGA), these authors achieved to show "how subgroups adapt within the team, without defining beforehand how many players and which specific players belong to each subgroup" (Carrilho et al., 2020, p11).

Another possible way to reconcile researchers' reductionist and holistic perspectives is through the patterns obtained by "passing network metrics" (Pedro Passos, Keith Davids, et al., 2011). These patterns can be visually represented by a graph where the "nodes' positions are represented by the player's field position [...] sized according to the closeness centrality, and collared based on betweenness scores" (Bruno Gonçalves et al., 2017, p7). In this type of method, the intensity of the connections between players is represented by the width of the edges which are proportional to the number of passes successfully performed between two teammates (Gama et al., 2014). This approach was the basis, for example, to identify and compare coaching styles in professional football, using a principal component analysis technique (Immler et al., 2021).

In another approach, the degeneracy in sports teams was inspected through the examination of simplices transformations, using multilevel hypernetworks to capture cooperative and competitive interactions at different spatial scales (João Ramos et al., 2017)). In fact, following a multilevel hypernetworks approach, as exemplified by Pereira and colleagues (Pereira et al., 2021), is possible to quantify the variability of successive "hypergraphs" (from a "simplex" to the next), achieving a way to measure players' interactions by a multi-layer decomposition of its dynamics from macro level (a full match) to meso (clusters of players, transitions and teams), to micro (individual players).

Finally, a very promising way to investigate players' interactions and the functional effects from their combined effort is precisely exploring the already mentioned property of synergies that are linked to players' combination or *division of labour* (Corning, 2003). This is a synergy property that is also known as "sharing patterns" (M. Latash, 2008), or "interpersonal linkages", i.e., "the specific contribution of each element to a group task" (D. Araújo and K. Davids, 2016, p8). In fact, the joint analysis of all individuals' behaviours "can translate group behaviour as all players constrain and are constrained by the entire dynamic system that they compose" (Duarte Araújo, João Ramos, and R. Lopes, 2016, ch12). In operational terms, this property has the potential to test the synergism hypothesis in team sports from a reductionist / holistic hybrid point of view, "by measures of heat maps, major ranges, player-to-locus distance and Voronoi cells" (Duarte Araújo, João Ramos, and R. Lopes, 2016, ch12).

For Araújo and Davids (2016, p9), "heat maps provide a clear picture of the distribution of each player on the field", being a method widely used in graphic terms in football television broadcasts, but also in some scientific studies (Link and Hoernig, 2017; Fernández, Luke Bornn, and Dan Cervone, 2019). On the other hand, as used by Yue and colleagues (2008), "major ranges imply the calculation of an ellipse centered at each player's locus and with semi-axes being the standard deviations in the x- and y-directions, respectively", making it "possible to identify preferred spatial positions, major roles for each player and playing styles" (D. Araújo and K. Davids, 2016, p9). Similar approaches are the "positional variability" (Moura, Santana, et al., 2015) or the "player-to-locus distance" (Pedro Silva, Aguiar, et al., 2014), a metric inspired by the idea that sports team players can show a "tendency to oscillate around a given point or locus" (McGarry et al., 2002, p778), informing about the team's global (self-)organization in a given time scale.

Lastly, from the perspective of Araújo and Davids (D. Araújo and K. Davids, 2016, p9) the Voronoi cells, because they "contains all spatial points that are nearer to the player to whom that cell is allocated than to the other players", have the potential to quantify this property of collective synergies. Despite its limitations (Efthimiou, 2021), Voronoi cells are "spatial measures [able to] emphasise the individual playing areas attributed to each player on a team" (Duarte Araújo, Keith Davids, Diniz, et al., 2015, p216), potentially inferring perceived spatial affordances (Gold, 1995).

Therefore, through Voronoi diagrams (VD), is possible to measure the local "sphere of influence" (Taki and J. i. Hasegawa, 2000) of each player (e.g., the ball carrier), in relation to the global context of the team and the match. Several metrics based on VD are promising ways to test the "synergism hypothesis" in football teams, linking the functional effects (synergies' payoffs) with the *glocal* (Robertson, 1995) patterns emerging from players' interactions. Beyond VD simple measurements (Fonseca et al., 2012; Rein, Raabe, and Memmert, 2017), the integration of players' speeds and trajectories in the computation, enabled more complex metrics to assess players' interpersonal linkages. These include "dominant regions" (Taki and J.-i. Hasegawa, 2000; Fujimura and Sugihara, 2005; Nakanishi et al., 2009), the "player's reachable region" (Gudmundsson and Wolle, 2014) or the "player's area of influence" (Javier Fernandez and Luke Bornn, 2018).

In conclusion, despite all these metrics already available for football performance research, to test the "synergism hypothesis" is necessary to still go through a long path. In fact, the big challenge is in progress to establish the links between the functional effects of the team synergies and the patterns that emerge from players' interactions in the match and / or training environments. Even more if one assumes the quest to investigate football environments not only from a reductionist or holistic approach but from a hybrid perspective that focuses on both parts and wholes. For this reason, it will be necessary to develop the existing metrics, imagine new ones and refine the methods that can allow assessing the patterns emerging from players' interactions and inherent performance (payoffs). In this particular, it will be determinant to be also supported in Gibson's theory of affordances. In fact, players' interactions emerge from the opportunities for action that are perceived by the players, in an always-changing match landscape. Only with this background that shapes players' decisions can be possible to understand team synergies. For example, to know how teams collectively achieve to dominate the game space, maintain ball possession or reach the best location to shoot. Being a low-score game, these are examples of performance indicators (payoffs) that should be investigated as a consequence of football players' interactions. This is why we argue that only by deepening our knowledge about team synergies and players' interactions emerging from the perceived affordances, it will be possible to progress in understanding the football team's performance.

## References


Akenhead, Richard et al. (2013). "Diminutions of acceleration and deceleration output during professional football match play". In: *Journal of Science and Medicine in Sport* 16.6, pp. 556–561. DOI: 10.1016/j.jsams.2012.12.005.

Altmann, Stefan et al. (2021). "Match-related physical performance in professional soccer: Position or player specific ?" In: *PLoS ONE* 16.9, pp. 22–24. DOI: doi.org/10.1371/journal.pone.0256695Editor:.

Aquino, Rodrigo L.Q.T. et al. (2016). "Periodization training focused on technical-tactical ability in young soccer players positively affects biochemical markers and game performance". In: *Journal of Strength and Conditioning Research* 30.10, pp. 2723–2732. DOI: 10.1519/JSC.0000000000001381.

Araújo, D. and K. Davids (2016). "Team synergies in sport: Theory and measures". In: *Frontiers in Psychology* 7.SEP, pp. 1–13. DOI: 10.3389/fpsyg.2016.01449Team.

Araújo, D., K. Davids, et al. (2003). "Emergence of sport skills under constraints". In: *Skill Acquisition in Sport: Research, Theory and Practice*. Ed. by A.M. Williams and N.J. Hodges. London: Ro. London: Routledge, pp. 433–458.

Araújo, D., P. Silva, and J. Ramos (2014). "Affordance-based decisions guide team synergies during match performance". In: *Research in Physical Education, Sport and Health* 3.1, pp. 19–26.

Araújo, Duarte, Keith Davids, Ana Diniz, et al. (2015). "Ecological dynamics of continuous and categorical decision-making: The regatta start in sailing". In: *European Journal of Sport Science* 15.3, pp. 195–202. DOI: 10.1080/17461391.2014.928749.

Araújo, Duarte, Keith Davids, and Pedro Passos (2005). "Ecological Validity, Representative Design and Correspondence between Experimental Task Constraints and Behavioral Settings Comment on Rogers, Kadar and Costall (2005)". In: *Ecological Psychology* 19.1, pp. 69–78.

Araújo, Duarte, João Ramos, and Rui Lopes (2016). "Shared affordances guide interpersonal synergies in sport teams". In: *Interpersonal coordination and performance in social systems*. Routledge, pp. 183–196.

Arvind, Om (2020). *The Impact Of Cristiano Ronaldo's Departure On Real Madrid's Offense & Defense*.

Balague, Natàlia et al. (2013). "Overview of complex systems in sport". In: *Journal of Systems Science and Complexity* 26.1, pp. 4–13. DOI: 10.1007/s11424-013-2285-0.

Bangsbo, J. (Dec. 2015). "Training and testing the top-class soccer player". In: *Journal of Science and Medicine in Sport* 19, e78. DOI: 10.1016/j.jsams.2015.12.188.

Barnabé, Luís et al. (Aug. 2016). "Age-related effects of practice experience on collective behaviours of football players in small-sided games". In: *Human Movement Science* 48, pp. 74–81. DOI: 10.1016/j.humov.2016.04.007.

Barris, Sian and Chris Button (2008). "A review of vision-based motion analysis in sport". In: *Sports Medicine* 38.12, pp. 1025–1043. DOI: 10.2165/00007256-200838120-00006.

Bartlett, R., J. Wheat, and M. Robins (2007). "Is Movement Variability Important for Sports Biomechanists?" In: *Sports biomechanics* 6.2, pp. 224–243.

Bartlett, Roger et al. (2012). “Analysing team coordination patterns from player movement trajectories in soccer: Methodological considerations”. In: *International Journal of Performance Analysis in Sport* 12.2, pp. 398–424. DOI: 10.1080/24748668.2012.11868607.

Bernstein, N. (1967). *Coordination and Regulation of Movements*. New York: Pergamon Press.

Bishop, David John (2008). “An Applied Research Model for the Sport Sciences”. In: *Sports Medicine* 38.3, pp. 253–263. DOI: 10.2165/00007256-200838030-00005.

Bornn, L., D. Cervone, and J. Fernandez (2018). “Soccer analytics: Unravelling the complexity of “the beautiful game””. In: *Significance* 15(3).3, pp. 26–29.

Bourbousson, Jérôme, Carole Sève, and Tim McGarry (2010). “Space-time coordination dynamics in basketball: Part 2. the interaction between the two teams”. In: *Journal of Sports Sciences* 28.3, pp. 349–358. DOI: 10.1080/02640410903503640.

Bradley, PS and JD Ade (2018). “Are Current Physical Match Performance Metrics in Elite Soccer Fit for Purpose or is the Adoption of an Integrated Approach Needed?” In: *International Journal of Sports Physiology and Performance* 13.5, pp. 656–664.

Brito Souza, Diego et al. (2019). “A new paradigm to understand success in professional football: analysis of match statistics in LaLiga for 8 complete seasons”. In: *International Journal of Performance Analysis in Sport* 19.4, pp. 543–555. DOI: 10.1080/24748668.2019.1632580.

Bruton, Michaela and Nicholas O’Dwyer (2018). “Synergies in coordination: A comprehensive overview of neural, computational, and behavioral approaches”. In: *Journal of Neurophysiology* 120.6, pp. 2761–2774. DOI: 10.1152/jn.00052.2018.

Buchheit, Martin et al. (2014). “Integrating different tracking systems in football: multiple camera semi-automatic system, local position measurement and GPS technologies”. In: *Journal of Sports Sciences* 32:20, pp. 1844–1857. DOI: 10.1080/02640414.2014.942687.

Caetano, Fabio Giuliano et al. (2019). “Analysis of Match Dynamics of Different Soccer Competition Levels Based on The Player Dyads”. In: *Journal of Human Kinetics* 70.December, pp. 173–182. DOI: 10.2478/hukin-2019-0030.

Carling, Christopher (2013). “Interpreting physical performance in professional soccer match-play: Should we be more pragmatic in our approach?” In: *Sports Medicine* 43.8, pp. 655–663. DOI: 10.1007/s40279-013-0055-8.

Carling, Christopher et al. (2008). “The role of motion analysis in elite soccer: Contemporary performance measurement techniques and work rate data”. In: *Sports Medicine* 38.10, pp. 839–862. DOI: 10.2165/00007256-200838100-00004.

Carrilho, Daniel et al. (Sept. 2020). “Using optical tracking system data to measure team synergic behavior: Synchronization of player-ball-goal angles in a football match”. In: *Sensors (Switzerland)* 20.17, pp. 1–14. DOI: 10.3390/s20174990.

Clemente, Filipe Manuel, Duarte Araújo, and Keith Davids (2017). *What performance analysts need to know about research trends in Association Football (2012-2016)-A systematic review*.

Clemente, Filipe Manuel, Micael Santos Couceiro, et al. (2014). "Análise de jogo no Futebol: Métricas de avaliação do comportamento coletivo". In: *Motricidade* 10.1, pp. 14–26. DOI: 10.6063/motricidade.10(1).1517.

Clemente, Filipe Manuel and Rúben Filipe Rocha (2013). "Teaching and soccer training: An approach through a tactical perspective". In: *Journal of Physical Education and Sport* 13.1, pp. 14–18. DOI: 10.7752/jpes.2013.01003.

Cordovil, Rita et al. (2009). "The influence of instructions and body-scaling as constraints on decision-making processes in team sports". In: *European Journal of Sport Science* 9.3, pp. 169–179. DOI: 10.1080/17461390902763417.

Corning, Peter (1983). *The Synergism Hypothesis: A Theory of Progressive Evolution*. McGraw-Hill, New York.

— (1998). ""The synergism hypothesis": On the concept of synergy and its role in the evolution of complex systems". In: *Journal of social and evolutionary systems* 21.2, pp. 133–172.

— (2003). *Nature's magic: Synergy in evolution and the fate of humankind*. Cambridge University Press.

— (2008). "Holistic Darwinism: the new evolutionary paradigm and some implications for political science". In: *Politics and the Life Sciences* 27.1, pp. 22–54.

— (2010). *Holistic Darwinism*. University of Chicago Press.

— (2018). *Synergistic Selection: How Cooperation Has Shaped Evolution And The Rise Of Humankind*. WORLD SCIENTIFIC PUBLISHING CO PTE LTD.

Coupe, Tom, Olivier Gergaud, and Abdul Noury (2017). "Biases in Voting - The Case of the FIFA Best Player Award". In: *Oxford Bulletin of Economics & Statistics* 80.2.

Coutinho, Diogo et al. (2018). "Exploring the effects of mental and muscular fatigue in soccer players' performance". In: *Human Movement Science* 58.March, pp. 287–296. DOI: 10.1016/j.humov.2018.03.004.

Czyż, S. H. et al. (2016). "Participation in team sports can eliminate the effect of social loafing". In: *Perceptual and Motor Skills* 123.3, pp. 754–769.

Davids, Keith and Duarte Araújo (2010). "The concept of 'Organismic Asymmetry' in sport science". In: *Journal of Science and Medicine in Sport* 13.6, pp. 633–640. DOI: 10.1016/j.jsams.2010.05.002.

Davids, Keith, Duarte Araújo, and Rick Shuttleworth (2005). "Applications of Dynamical Systems Theory to Football". In: *Science and Football V: The Proceedings of the Fifth World Congress on Science and Football* i, pp. 537–550.

Davis, Bent and Dennis Sumara (2010). "Enabling constraints: using complexity research to strcuture collective". In: *(More) Teaching Games for Understanding: Moving globally*. Human Kinetics, pp. 105–120.

de la Fuente Vizcay, C. E. and A. G. Sarmiento (2020). "Efecto de ringelmann y su relación con el rendimiento de los remeros indoor". In: *Educación y pedagogía en las ciencias de la cultura física y el deporte*. Red Iberoamericana de Pedagogía, pp. 223–229.

Duarte, Ricardo, Duarte Araújo, Vanda Correia, and Keith Davids (2012). "Sports Teams as Superorganisms". In: *Sports Medicine* 42.8, p. 1. DOI: 10.2165/11632450-000000000-00000.

Duarte, Ricardo, Duarte Araújo, Vanda Correia, Keith Davids, et al. (2013). "Competing together: Assessing the dynamics of team-team and player-team synchrony in professional association football". In: *Human Movement Science* 32.4, pp. 555–566. DOI: 10.1016/j.humov.2013.01.011.

Duarte, Ricardo, Bruno Travassos, et al. (2013). "The influence of manipulating the defensive playing method on collective synchrony of football teams". In: *Performance Analysis of Sport IX* 1, pp. 65–70. DOI: 10.4324/9780203080443.

Duch, Jordi, Joshua S. Waitzman, and Luís A. Nunes Amaral (2010). "Quantifying the performance of individual players in a team activity". In: *PLoS ONE* 5.6, pp. 1–8. DOI: 10.1371/journal.pone.0010937.

Efthimiou, Costas J. (2021). "The Voronoi Diagram in Soccer: a theoretical study to measure dominance space". In: *arXiv preprint arXiv:2107.05714.*, pp. 1–32. arXiv: 2107.05714.

Fajen, Brett R., Michael A. Riley, and Michael T. Turvey (2009). "Information, affordances, and the control of action in sport". In: *International Journal of Sport Psychology* 40.1, pp. 79–107.

Fernandez, Javier and Luke Bornn (2018). "Wide Open Spaces : A statistical technique for measuring space creation in professional soccer". In: *MIT Sloan Sports Analytics Conference* May, pp. 1–19.

Fernández, Javier, Luke Bornn, and Dan Cervone (2019). "Decomposing the Immeasurable Sport: A deep learning expected possession value framework for soccer". In: *MIT Sloan Sports Analytics Conference*, pp. 1–18.

Filetti, Cristoforo et al. (2017). "A Study of Relationships among Technical, Tactical, Physical Parameters and Final Outcomes in Elite Soccer Matches as Analyzed by a Semiautomatic Video Tracking System". In: *Perceptual and Motor Skills* 124.3, pp. 601–620. DOI: 10.1177/0031512517692904.

Folgado, H. et al. (2012). "Length, width and centroid distance as measures of teams tactical performance in youth football". In: *Eur. J. Sport Sci.* 14.Supple.1, S487–S492. DOI: 10.1080/17461391.2012.730060.

Folgado, Hugo et al. (May 2019). "Towards the use of multidimensional performance indicators in football small-sided games: the effects of pitch orientation". In: *Journal of Sports Sciences* 37.9, pp. 1064–1071. DOI: 10.1080/02640414.2018.1543834.

Fonseca, Sofia et al. (2012). "Spatial dynamics of team sports exposed by Voronoi diagrams". In: *Human Movement Science* 31.6, pp. 1652–1659. DOI: 10.1016/j.humov.2012.04.006.

Frank, T. D. and M. J. Richardson (2010). "On a test statistic for the Kuramoto order parameter of synchronization: An illustration for group synchronization during rocking chairs". In: *Physica D: Nonlinear Phenomena* 239.23-24, pp. 2084–2092. DOI: 10.1016/j.physd.2010.07.015.

Frencken, W. and K. Lemmink (2008). "Team kinematics of small-sided soccer games. A systematic approach". In: *Science and football VI: Proceedings of the 6th World*. Ed. by In T. Reilly & F. Korkusuz (Eds.) September. New York: Routledge, pp. 161–166.

Frencken, Wouter, Koen Lemmink, et al. (2011). "Oscillations of centroid position and surface area of soccer teams in small-sided games". In: *European Journal of Sport Science* 11.4, pp. 215–223. DOI: 10.1080/17461391.2010.499967.

Frencken, Wouter, Harjo de Poel, et al. (2012). "Variability of inter-team distances associated with match events in elite-standard soccer". In: *Journal of Sports Sciences* 30.12, pp. 1207–1213. DOI: 10.1080/02640414.2012.703783.

Fujimura, A. and K. Sugihara (2005). “Geometric analysis and quantitative evaluation of sport teamwork”. In: *Systems and Computers in Japan* 36.6, pp. 49–58.

Fuller, R. (1982). *Synergetics: Explorations in the geometry of thinking*. Estate of R. Buckminster Fuller.

Gama, José et al. (2014). “Network analysis and intra-team activity in attacking phases of professional football”. In: *International Journal of Performance Analysis in Sport* 14.3, pp. 692–708. DOI: 10.1080/24748668.2014.11868752.

Garganta, Júlio (2009). “Trends of tactical performance analysis in team sports: bridging the gap between research, training and competition.” In: *Revista Portuguesa de Ciências do Desporto* 9.1, pp. 81–89.

Garganta, Júlio and Jean Francis Gréhaigne (1999). “Abordagem Sistêmica Do Jogo De Futebol: Moda Ou Necessidade?” In: *Movimento (ESEFID/UFRGS)* 5.10, pp. 40–50. DOI: 10.22456/1982-8918.2457.

Gelfand, I. M. and M. L. Latash (1998). “On the problem of adequate language in motor control.” In: *Motor control* 2.4, pp. 306–313. DOI: 10.1123/mcj.2.4.306.

Gibson, J. (1979). *The ecological approach to visual perception*. Boston: Houghton, Mifflin and Company.

Goes, F. R. et al. (2020). “Unlocking the potential of big data to support tactical performance analysis in professional soccer: A systematic review”. In: *European Journal of Sport Science* 0.0, pp. 1–16. DOI: 10.1080/17461391.2020.1747552.

Goes, Floris R., Michel S. Brink, et al. (2020). “The tactics of successful attacks in professional association football: large-scale spatiotemporal analysis of dynamic subgroups using position tracking data”. In: *Journal of Sports Sciences*. DOI: 10.1080/02640414.2020.1834689.

Goes, Floris R., Matthias Kempe, et al. (Mar. 2019). “Not Every Pass Can Be an Assist: A Data-Driven Model to Measure Pass Effectiveness in Professional Soccer Matches”. In: *Big Data* 7.1, pp. 57–70. DOI: 10.1089/big.2018.0067.

Gold, Christopher (1995). “Advantages of the Voronoi spatial model”. In: *Proceedings of Eurocarto XII*. Copenhagen, pp. 1–10.

Gonçalves, B. et al. (July 2016). “Effects of emphasising opposition and cooperation on collective movement behaviour during football small-sided games”. In: *Journal of Sports Sciences* 34.14, pp. 1346–1354. DOI: 10.1080/02640414.2016.1143111.

Gonçalves, Bruno et al. (2017). “Exploring team passing networks and player movement dynamics in youth association football”. In: *PLoS ONE* 12.1, pp. 1–13. DOI: 10.1371/journal.pone.0171156.

Gonçalves, Bruno V et al. (2014). “Effect of player position on movement behaviour, physical and physiological performances during an 11-a-side football game.” In: *Journal of Sports Sciences* 32.2, pp. 191–199. DOI: 10.1080/02640414.2013.816761.

Gorman, Jamie C., Polemnia G. Amazeen, and Nancy J. Cooke (2010). “Team coordination dynamics”. In: *Nonlinear Dynamics, Psychology, and Life Sciences* 14.3, pp. 265–289.

Gréhaigne, J. (1992). *L’organisation du jeu en Football*. Éditions Actio.

Gréhaigne, J.F., B. Mahut, and A. Fernandez (2001). “Qualitative observation tools to analyse soccer”. In: *International Journal of Performance Analysis in Sport* 1.1, pp. 52–61. DOI: 10.1080/24748668.2001.11868248.

Gréhaigne, Jean Francis, Daniel Bouthier, and Bernard David (1997). “Dynamic-system analysis of opponent relationships in collective actions in soccer”. In: *Journal of Sports Sciences* 15.2, pp. 137–149. DOI: 10.1080/026404197367416.

Gudmundsson, Joachim and Michael Horton (2017). “Spatio-temporal analysis of team sports”. In: *ACM Computing Surveys* 50.2. DOI: 10.1145/3054132. arXiv: 1602.06994.

Gudmundsson, Joachim and Thomas Wolle (2014). “Football analysis using spatio-temporal tools”. In: *Computers, Environment and Urban Systems* 47, pp. 16–27. DOI: 10.1016/j.compenvurbsys.2013.09.004.

Haken, H., J. A.S. Kelso, and H. Bunz (1985). “A theoretical model of phase transitions in human hand movements”. In: *Biological Cybernetics* 51.5, pp. 347–356. DOI: 10.1007/BF00336922.

Haken, Hermann (1983). *Synergetics: An Introduction*. Springer-Verlag. DOI: 10.1007/978-3-642-88340-8.

Headrick, Jonathon et al. (2012). “Proximity-to-goal as a constraint on patterns of behaviour in attacker–defender dyads in team games”. In: *Journal of Sports Sciences* 30.3, pp. 247–253. DOI: 10.1080/02640414.2011.640706.

Heuzé, J. P. and P. C. Brunel (2003). “Social loafing in competitive context”. In: *International Journal of Sport and Exercise Psychology* 1.3, pp. 246–263. DOI: 10.1080/1612197X.2003.9671717.

Hirotsu, Nobuyoshi et al. (2009). “Modeling Tactical Changes of Formation in Association Football as a Zero-Sum Game”. In: *Journal of Quantitative Analysis in Sports* 5.

Immler, Sebastian et al. (2021). “Guardiola, Klopp, and Pochettino: The Purveyors of What? The Use of Passing Network Analysis to Identify and Compare Coaching Styles in Professional Football”. In: *Frontiers in Sports and Active Living* 3.October, pp. 1–9. DOI: 10.3389/fspor.2021.725554.

Kelso, J. A.Scott (2022). “On the coordination dynamics of (animate) moving bodies”. In: *Journal of Physics: Complexity* 3.3, pp. 1–16. DOI: 10.1088/2632-072X/ac7caf.

— (2017). “Principles of Coordination: Synergies of Synergies!” In: *Complex Systems in Sport, International Congress. Linking Theory and Practice*. Ed. by Carlota Torrents, Pedro Passos, and Francesc Cos, pp. 13–16.

Kelso, Scott (2009). “Coordination Dynamics”. In: *Encyclopedia of Complexity and Systems Science*. Ed. by R. Meyers. Springer, pp. 1537–1567. DOI: 10.1007/978-3-642-27737-5.

Kiefer, Adam W. et al. (2017). “Quantifying and modeling coordination and coherence in pedestrian groups”. In: *Frontiers in Psychology* 8.JUN, pp. 1–13. DOI: 10.3389/fpsyg.2017.00949.

Koliba, Christopher et al. (2022). “Complexity theory and systems analysis”. In: *Handbook on theories of governance*. Edward Elgar Publishing.

Lago-Peñas, Carlos and Alexandre Dellal (2010). “Ball possession strategies in elite soccer according to the evolution of the match-score: The influence of situational variables”. In: *Journal of Human Kinetics* 25.1, pp. 93–100. DOI: 10.2478/v10078-010-0036-z.

Lames, M., J. Ertmer, and F. Walter (2010). “Oscillations in football—order and disorder in spatial interactions between the two teams”. In: *International Journal of Sport Psychology* 41.4, pp. 85–86.

Latash, M. (2008). *Synergy*. New York and Oxford: University Press.

Latash, Mark and Vladimir Zatsiorsky (2015). *Biomechanics and motor control. Defining central concepts*. Academic Press.

Latash, Mark L. (2021). “One more time about motor (and non-motor) synergies”. In: *Experimental Brain Research* 239.10, pp. 2951–2967. DOI: 10.1007/s00221-021-06188-4.

Latash, Mark L., John P. Scholz, and Gregor Schöner (2007). “Toward a new theory of motor synergies”. In: *Motor Control* 11.3, pp. 276–308. DOI: 10.1123/mcj.11.3.276.

Lepschy, Hannes, Hagen Wäsche, and Alexander Woll (2018). “How to be Successful in Football: A Systematic Review”. In: *The Open Sports Sciences Journal* 11.1, pp. 3–23. DOI: 10.2174/1875399x01811010003.

Link, Daniel and Martin Hoernig (2017). “Individual ball possession in soccer”. In: *PLoS ONE* 12.7, pp. 1–15. DOI: 10.1371/journal.pone.0179953.

Lobo, Luis Freitas (2019). *O Futebol com que Sonhei*. Contraponto Editores.

Lopes, José E. et al. (2012). “Instructional constraints on movement and performance of players in the penalty kick”. In: *International Journal of Performance Analysis in Sport* 12.2, pp. 311–345. DOI: 10.1080/24748668.2012.11868602.

López-felip, Maurici A and Till D Frank (2017). “Synchronization Assessment for Collective Behavior”. In: *CogSci*, pp. 706–710.

Low, Benedict, Gabriel Vilas Boas, et al. (2018). “Exploring the effects of deep-defending vs high-press on footballers’ tactical behaviour, physical and physiological performance: A pilot study”. In: *Motriz. Revista de Educacao Fisica* 24.2, pp. 1–7. DOI: 10.1590/S1980-6574201800020009.

Low, Benedict, Diogo Coutinho, et al. (Feb. 2020). “A Systematic Review of Collective Tactical Behaviours in Football Using Positional Data”. In: *Sports Medicine*, pp. 1–43. DOI: 10.1007/s40279-019-01194-7.

Machado, João Cláudio et al. (Oct. 2016). “The influence of rules manipulation on offensive patterns during small-sided and conditioned games in football”. In: *Motriz. Revista de Educacao Fisica* 22.4, pp. 290–298. DOI: 10.1590/S1980-6574201600040012.

Marsh, Kerry L. et al. (2006). “Contrasting approaches to perceiving and acting with others”. In: *Ecological Psychology* 18.1, pp. 1–38. DOI: 10.1207/s15326969eco1801_1.

Mason, Mark (2009). *Complexity Theory and the Philosophy of Education*, pp. 1–239. DOI: 10.1002/9781444307351.

Matesanz, David et al. (2018). “Transfer market activities and sportive performance in European first football leagues: A dynamic network approach”. In: *PLoS ONE* 13.12, pp. 1–16. DOI: 10.1371/journal.pone.0209362.

McGarry, Tim et al. (2002). “Sport competition as a dynamical self-organizing system”. In: *Journal of Sports Sciences* 20.10, pp. 771–781. DOI: 10.1080/026404102320675620.

McGuckian, Thomas B., Michael H. Cole, and Gert Jan Pepping (2018). “A systematic review of the technology-based assessment of visual perception and exploration behaviour in association football”. In: *Journal of Sports Sciences* 36.8, pp. 861–880. DOI: 10.1080/02640414.2017.1344780.

Mcinerney, C. (2017). “Determining spatio-temporal metrics that distinguish play outcomes in field hockey”. PhD thesis. Sheffield Hallam University (UK).

Merlin, Murilo et al. (2020). “Exploring the determinants of success in different clusters of ball possession sequences in soccer”. In: *Research in Sports Medicine* 28.3, pp. 339–350. DOI: 10.1080/15438627.2020.1716228.

Mitchell, Sandra D. (2012). “Emergence: Logical, functional and dynamical”. In: *Synthese* 185.2, pp. 171–186. DOI: 10.1007/s11229-010-9719-1.

Montanari, F., G. Silvestri, and E. Gallo (2008). “Team Performance Between Change and Stability: The Case of the Italian Serie A”. In: *Journal of Sport Management* 22.6.

Morillo-Baro, Juan P., Rafael E. Reigal, and Antonio Hernández-Mendo (July 2020). “Origin and modifications of the geometrical centre to assess team behaviour in team sports: a systematic review”. In: *RICYDE: Revista Internacional de Ciencias del Deporte* 16.61, pp. 318–329. DOI: 10.5232/ricyde.

Morin, Edgar (1999). *O método II: A vida da vida*. Mem Martins: Publicacoes Europa-America.

— (2008). *On complexity: Advances in systems theory, complexity, and the human sciences*. New York: Hampton Press.

Morsinkhof, J B (2014). “The influence of social identity theory on voting behavior in the FIFA Ballon d’Or competition”. PhD thesis. Bachelor’s thesis, University of Twente, pp. 1–7.

Moura, Felipe Arruda, Luiz Eduardo Barreto Martins, et al. (2012). “Quantitative analysis of Brazilian football players’ organisation on the pitch”. In: *Sports Biomechanics* 11.1, pp. 85–96. DOI: 10.1080/14763141.2011.637123.

Moura, Felipe Arruda, Juliana Exel Santana, et al. (Sept. 2015). “Analysis of Soccer Players’ Positional Variability during the 2012 UEFA European Championship: A Case Study”. In: *Journal of Human Kinetics* 47.1, pp. 225–236. DOI: 10.1515/hukin-2015-0078.

Mysterud, I. (2004). “Synergy: an idea whose time has come?” In: *Trends in Ecology & Evolution* 3.19, pp. 118–119.

Nakanishi, R. et al. (2009). “An approximate computation of the dominant region diagram for the real-time analysis of group behaviors”. In: *RoboCup*, pp. 228–239.

Olthof, Sigrid B.H., Wouter G.P. Frencken, and Koen A.P.M. Lemmink (July 2018). “Match-derived relative pitch area changes the physical and team tactical performance of elite soccer players in small-sided soccer games”. In: *Journal of Sports Sciences* 36.14, pp. 1557–1563. DOI: 10.1080/02640414.2017.1403412.

Orth, Dominic et al. (2014). “Effects of a defender on run-up velocity and ball speed when crossing a football”. In: *European Journal of Sport Science* 14.SUPPL.1, pp. 37–41. DOI: 10.1080/17461391.2012.696712.

Palut, Y. and P. Zanone (2005). “A dynamical analysis of tennis: Concepts and data”. In: *Journal of sports sciences* 23.10, pp. 1021–1032.

Papi, Enrica, Philip J Rowe, and Valerie M Pomeroy (2015). “Analysis of gait data in manifold space: The control of the centre of mass during gait”. PhD thesis. Imperial College London, pp. 1–14.

Passos, P., E. Lacasa, et al. (2020). “Capturing Interpersonal Synergies in Social Settings: An Example within a Badminton Cooperative Task”. In: *Nonlinear dynamics, psychology, and life sciences* 24.1, pp. 59–78.

Passos, P., J. Milho, and C. Button (2018). "Quantifying synergies in two-versus-one situations in team sports: An example from Rugby Union". In: *Behavior Research Methods* 50.2, pp. 620–629. DOI: 10.3758/s13428-017-0889-3.

Passos, Pedro, Duarte Araújo, and Keith Davids (2013). "Self-organization processes in field-invasion team sports implications for leadership". In: *Sports Medicine* 43.1, pp. 1–7. DOI: 10.1007/s40279-012-0001-1.

— (2016). "Competitiveness and the process of co-adaptation in team sport performance". In: *Frontiers in Psychology* 7.OCT, pp. 1–5. DOI: 10.3389/fpsyg.2016.01562.

Passos, Pedro, Duarte Araújo, Keith Davids, Luis Gouveia, et al. (2009). "Interpersonal pattern dynamics and adaptive behavior in multiagent neurobiological systems: Conceptual model and data". In: *Journal of Motor Behavior* 41.5, pp. 445–459. DOI: 10.3200/35-08-061.

Passos, Pedro, Duarte Araújo, Keith Davids, and Richard Shuttleworth (2008). "Manipulating Constraints to Train Decision Making in Rugby Union". In: *International Journal of Sports Science & Coaching* 3.1, pp. 125–140. DOI: 10.1260/174795408784089432.

Passos, Pedro, Keith Davids, et al. (2011). "Networks as a novel tool for studying team ball sports as complex social systems". In: *Journal of Science and Medicine in Sport* 14.2, pp. 170–176. DOI: 10.1016/j.jsams.2010.10.459.

Paul, DJ, PS Bradley, and GP Nassis (2015). "Factors Impacting Match Running Performances of Elite Soccer Players : Shedding Some Light on the Complexity". In: *International journal of sports physiology and performance* 10.4, pp. 516–519. DOI: doi.org/10.1123/IJSPP.2015-0029.

Pereira, Luis Ramada et al. (2021). "The Soccer Game, bit by bit: An information-theoretic analysis". In: *arXiv e-prints, arXiv-2102*. arXiv: 2102.11182.

Pinder, Ross A. et al. (2011). "Representative learning design and functionality of research and practice in sport". In: *Journal of Sport and Exercise Psychology* 33.1, pp. 146–155. DOI: 10.1123/jsep.33.1.146.

Pinto, C. (2014). "The emergence of team synchronization during the soccer match: understanding the influence of the level of opposition, game phase and field zone". PhD thesis.

Pol, Rafel et al. (2020). "Training or Synergizing? Complex Systems Principles Change the Understanding of Sport Processes". In: *Sports Medicine - Open* 6.1. DOI: 10.1186/s40798-020-00256-9.

Polozov, A. A. et al. (2019). "Calculation of the social laziness syndrome level indicators in the game of top-level sport teams". In: *AIP Conference Proceedings*. AIP Publishing LLC, 2186, No. 1, p. 050021.

Pratas, J Maria, A Volossovitch, and A Isabel Carita (2018). "Goal scoring in elite male football: A systematic review". In: *Journal of Human Sport and Exercise* 218.1, pp. 218–230. DOI: 10.14198/jhse.2018.131.19.

Procaccia, A., N. Shah, and M. Tucker (2014). "On the Structure of Synergies in Cooperative Games". In: *Proceedings of the AAAI Conference on Artificial Intelligence*, Vol. 28, No. 1.

Ramos, João et al. (2017). "Hypernetworks reveal compound variables that capture cooperative and competitive interactions in a soccer match". In: *Frontiers in Psychology* 8.AUG, pp. 1–12. DOI: 10.3389/fpsyg.2017.01379.

Reed, E. (1996). *Encountering the World: Toward an Ecological Psychology*. New York: Oxford University Press.

Rein, Robert, Dominik Raabe, and Daniel Memmert (Oct. 2017). ""Which pass is better?" Novel approaches to assess passing effectiveness in elite soccer". In: *Human Movement Science* 55, pp. 172–181. DOI: 10.1016/j.humov.2017.07.010.

Reindal, Solveig (1999). "Independence, Dependence, Interdependence: Some reflections on the subject and personal autonomy". In: *Disability & Society* 14.3, pp. 353–367. DOI: 10.1080/09687599926190.

Ribeiro, João et al. (Oct. 2019). "Exploiting Bi-Directional Self-Organizing Tendencies in Team Sports: The Role of the Game Model and Tactical Principles of Play". In: *Frontiers in Psychology* 10. DOI: 10.3389/fpsyg.2019.02213.

Richau, Lukas et al. (2019). "Performance indicators in football: The importance of actual performance for the market value of football players". In: *Sciamus - Sport und Management*. Ed. by Freya Gassmann, Eike Emrich, and Christoph Rasche. January 2020, pp. 41–67.

Rico-González, Markel et al. (Apr. 2020). *The use of technology and sampling frequency to measure variables of tactical positioning in team sports: a systematic review*. DOI: 10.1080/15438627.2019.1660879.

Riley, Michael et al. (2011). "Interpersonal synergies". In: *Frontiers in Psychology* 2.MAR. DOI: 10.3389/fpsyg.2011.00038.

RMCSport (2021). *PSG-MONTPELLIER: QUAND MBAPPÉ RÂLE SUR LE BANC CONTRE NEYMAR*. (Visited on 09/26/2021).

Robalo, R. et al. (2021). "Are synergies continuously present in cyclical movements? An example with the basketball dribble task". In: *Human Movement Science* 80.102883.

Robertson, R. (1995). "Glocalization: Time-space and homogeneity-heterogeneity". In: *Global modernities* 2.1, pp. 25–44.

Sampaio, Jaime E. et al. (2014). "Effects of pacing, status and unbalance in time motion variables, heart rate and tactical behaviour when playing 5-a-side football small-sided games". In: *Journal of Science and Medicine in Sport* 17.2, pp. 229–233. DOI: 10.1016/j.jsams.2013.04.005.

Santos, Rodrigo, Ricardo Duarte, et al. (2018). "Interpersonal Coordination in Soccer: Interpreting Literature to Enhance the Representativeness of Task Design, From Dyads to Teams". In: *Front. Psychol* 9.2550. DOI: 10.3389/fpsyg.2018.02550.

Santos, Rodrigo and Pedro Passos (2021). "A Multi-Level Interdependent Hierarchy of Interpersonal Synergies in Team Sports: Theoretical Considerations". In: *Frontiers in Psychology* 12.December, pp. 10–13. DOI: 10.3389/fpsyg.2021.746372.

Sarmento, Hugo et al. (2014). "Match analysis in football: a systematic review". In: *Journal of Sports Sciences* 32.20, pp. 1831–1843. DOI: 10.1080/02640414.2014.898852.

Schöllhorn, W. (2003). "Coordination dynamics and its consequences on sports". In: *International Journal of Computer Science in Sport* 2.2, pp. 40–46.

Scholz, J. and G. Schöner (2014). "Use of the Uncontrolled Manifold (UCM) Approach to Understand Motor Variability, Motor Equivalence, and Self-motion". In: pp. 91–100. DOI: 10.1007/978-1-4939-1338-1.

Scholz, John P. and Gregor Schöner (1999). “The uncontrolled manifold concept: Identifying control variables for a functional task”. In: *Experimental Brain Research* 126.3, pp. 289–306. DOI: 10.1007/s002210050738.

Silva, P. (1995). “O lugar do corpo: elementos para uma cartografia fractal”. PhD thesis. Universidade do Porto.

Silva, Pedro (2014). “Shaping Tactical Behaviours in Football: An Ecological Dynamics Approach”. PhD thesis. Universidade do Porto, p. 214.

Silva, Pedro, Paulo Aguiar, et al. (2014). “Effects of Pitch Size and Skill Level on Tactical Behaviours of Association Football Players During Small-Sided and Conditioned Games”. In: *International Journal of Sports Science & Coaching* 9.5, pp. 993–1006.

Silva, Pedro, Ricardo Duarte, et al. (2014). “Field dimension and skill level constrain team tactical behaviours in small-sided and conditioned games in football.” In: *Journal of sports sciences* November, pp. 1–9. DOI: 10.1080/02640414.2014.961950.

Silva, Pedro, Júlio Garganta, et al. (2013). “Shared knowledge or shared affordances? insights from an ecological dynamics approach to team coordination in sports”. In: *Sports Medicine* 43.9, pp. 765–772. DOI: 10.1007/s40279-013-0070-9.

Silva, Pedro, Luís Vilar, et al. (2016). “Sports teams as complex adaptive systems: manipulating player numbers shapes behaviours during football small sided games”. In: *Springerplus* 5.Heim 1958, p. 191. DOI: 10.1186/s40064.

Slomka, Kajetan et al. (2015). “Intra-personal and inter-personal kinetic synergies during jumping”. In: *Journal of Human Kinetics* 49.1, pp. 75–88. DOI: 10.1515/hukin-2015-0110.

Smith, John Maynard (1998). *Evolutionary Genetics*. Oxford University Press.

Strong, Donald R and Donald A Phillips (2001). “Notes from the Underground . Communication and Control in the Rhizosphere”. In: *Plant Physiology* 127.3, pp. 727–730. DOI: 10.1104/pp.127.3.727.

Taki, Tsuyoshi and Jun ichi Hasegawa (2000). “Visualization of dominant region in team games and its application to teamwork analysis”. In: *Proceedings of Computer Graphics International Conference, CGI*, pp. 227–235. DOI: 10.1109/cgi.2000.852338.

Taki, Tsuyoshi and Jun-ichi Hasegawa (2000). “Quantitative measurement of teamwork in ball games using dominant region”. In: *ISPRS J Photogramm* XXXIII.1992, pp. 125–131.

Teodorescu, L. (1984). *Problemas de teoria e metodologia nos jogos desportivos*. Ed. by Ed. Horizonte. Lisboa.

Thomas, T. S. and W. D. Casebeer (2004). “Violent Non-State Actors : Countering Dynamic Systems”. In: *Strategic Insights* III.3.

Thorpe, R (2011). “The Tracking of Morning Fatigue Status Across In-Season Training Weeks in Elite Soccer Players”. In: *Int. J. Sport Nutr. Exerc. Metab.* January, pp. 1–44. DOI: 10.1123/ijspp.2015-0012. arXiv: 1111.6189v1.

Travassos, B. et al. (2011). “Interpersonal coordination and ball dynamics in futsal (indoor football)”. In: *Human Movement Science* 30.6, pp. 1245–1259. DOI: 10.1016/j.humov.2011.04.003.

Travassos, Bruno, Duarte Araújo, et al. (2012). “Improving passing actions in team sports by developing interpersonal interactions between players”. In: *International Journal of Sports Science and Coaching* 7.4, pp. 677–688. DOI: 10.1260/1747-9541.7.4.677.

Travassos, Bruno, Ricardo Duarte, et al. (2012). “Practice task design in team sports: Representativeness enhanced by increasing opportunities for action”. In: *Journal of Sports Sciences* 30.13, pp. 1447–1454. DOI: 10.1080/02640414.2012.712716.

Turvey, M. T. (2007). “Action and perception at the level of synergies”. In: *Human Movement Science* 26.4, pp. 657–697. DOI: 10.1016/j.humov.2007.04.002.

Vaughan, J. et al. (2017). “Ecological theories, non-linear practise and creative collaboration at AIK Football Club”. In: *Complex Systems in Sport, International Congress Linking Theory and Practice*, pp. 177–180.

Vaz, Daniela V. et al. (2019). “Coordination in adults with neurological impairment – A systematic review of uncontrolled manifold studies”. In: *Gait and Posture* 69, pp. 66–78. DOI: 10.1016/j.gaitpost.2019.01.003.

Vilar, Luís et al. (2012). “The need for ’representative task design’ in evaluating efficacy of skills tests in sport: A comment on Russell, Benton and Kingsley (2010)”. In: *Journal of Sports Sciences* 30.16, pp. 1727–1730. DOI: 10.1080/02640414.2012.679674.

Wright, Robert (2021). “Applying Game Theory Models to Athletic Contests”. In: *Academia Letters*. DOI: 10.20935/al681.

Yue, Z. et al. (2008). “Mathematical analysis of a soccer game. Part I: Individual and collective behaviors”. In: *Studies in applied mathematics* 121.3, pp. 223–243.

## Chapter 3

# Voronoi diagrams as a means to capture football team's synergies: from positional data to match analysis and training design

Caldeira, N., Lopes, R.J. & Araújo, D. (Under submission: International Journal of Sports Science & Coaching)

## Abstract

Football team performance is not the sum of individual players' performances. The uncertain outcome results from complex interactions that transform every match in a nonlinear dynamic system. Assessing players' and teams' collective behaviour is a chief task of football coaches and other practitioners notably in match analysis and the design of representative training exercises. To assess players' dynamic interactions, we argued that a functional approach to spatial dynamics, by means of Voronoi diagrams, can capture players' joint work (synergies). This claim is grounded in the ecological dynamics' theoretical framework, which searches for quantitative metrics that capture the intentionality of players' behaviour. This paper reviews how the measurement of Voronoi diagrams can capture the properties of the synergies resulting from the interaction of the elements in different types of systems, including football. We found some gaps in the measurement and understanding of football team synergies. We argue that players' (inter)actions to achieve teams' goals emerge from the affordances perceived (e.g., space dominance). Circularly, players' interactions modify the game perceptual landscape, in acting-perceiving cycles constrained by players' intentionality, which Voronoi diagrams can capture. We believe that using Voronoi diagrams-based tools also reduces the gap between research and coaches' practice, especially in high-level teams where positional data is highly available



## Keywords

Voronoi diagrams, Team synergies, Players' interaction, Tactical performance, Space dominance, Training design, Match analysis.

## 3.1 Introduction

Every football scientist or coach would like to establish a link between "performance indicators" and match outcomes (Herold et al., 2021). However, as a "low score" (Sarmento et al., 2014) "invasion game" (Kirk and MacPhail, 2002), a football match is marked by nonlinear interactions (Mateus, 2005), e.g., uncertain outcomes, sensitivity to initial conditions or nonlinear behaviour (Passos, Duarte Araújo, Keith Davids, et al., 2009). Consequently, football is a complex dynamic system (Keith Davids, Duarte Araújo, and Shuttleworth, 2005), where the overall team's performance can not be understood by the sum of players' individual performances (Coupe, Gergaud, and Noury, 2017). Players' individual performances cannot linearly cause a match outcome, such as happens with distances covered at different speed thresholds (Carling, 2013; Russell et al., 2016) or the number of passes of a given individual player (Hughes and Bartlett, 2002).

Therefore, a more complex approach to investigate football teams' performance is needed (Paul, Bradley, and Nassis, 2015; Bradley and Ade, 2018). The ecological dynamics approach argues that players' coordinated (inter)actions emerge under constraints (Newell, 1986), guided by *affordances* (Gibson, 1979), i.e., by the *opportunities for action* directly perceived in the match (Duarte Araújo, Keith Davids, and Hristovski, 2006). In the context of team sports, these ideas were taken to imply that the more successful teams are composed of players who have learned to perceive and act upon *shared affordances* (Pedro Silva et al., 2013). As highlighted by Araújo and Davids (2016), shared affordances guide the coordinated effort of their players into a synergy (D. Araújo, P. Silva, and J. Ramos, 2014). Therefore, a team synergy is a physical process that realizes a task goal (function) linking players by means of ambient information (D. Araújo and K. Davids, 2016). From this perspective, players coordinated actions establish functional synergies which could explain collective performance (Passos, Duarte Araújo, and Keith Davids, 2016). Discussing synergies, Corning uses a broad definition of synergy as the "*functional effects that are jointly created and that are not otherwise attainable*" (Corning, 2018, ch2). This definition of "*working together*" (literally the Greek translation of "synergy"), implies that every system formed by several parts that are doing a "function" can reveal synergies. However, arguably (Latash, 2008), Corning's hypothesis sustains a consistent vision about its role in the evolution of life and other complex systems (Corning, 2010). In this paper, we argue that the team synergy theoretical hypothesis (D. Araújo and K. Davids, 2016) can underpin research around football teams' performance when the quantification methods are grounded in a *glocal* approach (R. Robertson, 1995; Caldeira, 2013), that integrates the local details around players with a global view of the match landscape. Operationally, we argue that compound variables from Voronoi diagrams can capture different properties of team synergies.

## 3.2 Quantification methods to assess teams' synergies

If football team synergies support the performance of high-level football teams, it is possible to capture synergies properties physically, e.g., by collecting players' positional data extracted from football matches. Several team measures are already available such as teams' convex-hull (Moura et al., 2012), stretch index (Ricardo Duarte, Duarte Araújo, Correia, et al., 2013) or centroid (Frencken et al., 2011), used to understand how players cooperate to achieve a collective spatial functional advantage (e.g., by controlling the dispersion of players in different phases of the game). Over the last decade, the synchronization among players (using distances or angles) was also measured (Ricardo Duarte, 2012; Ricardo Duarte, Duarte Araújo, Freire, et al., 2012; Headrick et al., 2012; Travassos, Ricardo Duarte, et al., 2012; Pedro Silva, 2014; Folgado et al., 2018; Carrilho et al., 2020). Moreover, a global picture of the players' interactions through "passing networks" was used by several authors (Passos, Keith Davids, et al., 2011; Clemente et al., 2015; Gonçalves et al., 2017; João Ramos, R. J. Lopes, and Duarte Araújo, 2018), to understand the intensity of the connections between players and to compare different team tactical formations (McLean et al., 2018) or coaching styles (Immler et al., 2021). More complex network metrics such as those from hypernetworks (João Ramos, R. J. Lopes, Marques, et al., 2017; Ribeiro, R. Lopes, et al., 2020), where temporary cooperative – competitive synergies can be measured and reveal players' intentionality (i.e., purposefulness towards components of the match context, e.g., target area) on the pitch which emerges from local interactions (perception-action cycles).

However, positional data can also be used to calculate the connections among players and their nearest neighbours by *Delauney triangulations* (DT) connecting each point (player) with its nearest local neighbours. A DT respect the condition that all the circumcircles of all the triangles in the net are empty, permitting consequently to compute Voronoi diagrams (Chiu, 2003). As the circumcentres of DT are the vertices of the *Voronoi diagram* (VD), these allow determining the "unique limiting convex polygon such that all points within a point's polygon are closer to this point than all the other points" (S. Kim, 2004, p233).

In a VD, a Voronoi cell of a given player corresponds to the game space around each player, being functionally considered his/her main "sphere of influence" (Taki and J.-i. Hasegawa, 2000), "space control" (R. Rein et al., 2016) or "*space dominance*", as we prefer to designate in line with (2021). From our point of view, players' "space dominance" can be used to understand their perception of affordances (possibilities for action) in the match, constraining the emergence of team synergies, both in a *local* (e.g., around the ball carrier) or *global* scale (e.g., movement of both teams), as a dynamic system (Keith Davids, Duarte Araújo, and Shuttleworth, 2005). Consequently, such spatial analysis can reveal opportunities that emerge from the "collective work" (synergies) of a team pursuing some tactical purpose (function).

## 3.3 Synergistic properties captured through Voronoi diagrams

Over the last decades, football match analysis revealed that players-based physical and technical performance measures (Dellal et al., 2011) may be too "*reductionist*" (e.g., players' time-motion analysis profiles or their passing success rates), but also that a focus only in a global level (e.g., team's centroid or team's convex hull) are too "*holistic*" neglecting the description of the unique contributions of each player to team dynamics (Schöllhorn, 2003). The need to quantify the functional effects resulting from players' interactions on the field (synergies), at a simultaneously global and local match scale, persists. Therefore, investigate to capture "*glocal*" football performance (R. Robertson, 1995; Caldeira, 2013), implies physical methods that capture the *local* connections of each player with his/her nearest neighbours but considering the entire *global* match landscape.

Using the increasingly available player positional data (Sands et al., 2017; Robert Rein and Memmert, 2016), we argue that to capture "*glocal*" football performance can be done by solving the problem of finding the convex hull of a set of points (group of players) in the pitch bidimensional space, i.e., through a "Delaunay tessellation" (Chiu, 2003) that connects every player with his/her nearest neighbours (Barry Boots and Getis, 2020). Moreover, because the circumcentres of "Delaunay triangles" are the vertices of the correspondent "Voronoi diagram" (VD), these polygons can provide information about each player's "dominant space" (Taki and J.-i. Hasegawa, 2000; Efthimiou, 2021), using the area of each player Voronoi cell (VC). For a team, the sum of all VC of its players indicates its territorial dominance over the opponent (Fonseca et al., 2012; António Lopes et al., 2015). Nevertheless, beyond the cell areas, several other metrics can be extracted from a VD (Okabe, B. Boots, and Sugiharam, 2000), such as cell elongation, eccentricity, or neighbourhood features (Amores and Vasardani, 2018). As already tested in the sports context (Fonseca et al., 2012), a VD allows to quantify the interactions of each player with their neighbours (e.g., by the edges and vertices properties of a VC and adjacent cells), for example, to automatically identify a team tactical formation from players' positional data (Narizuka and Yamazaki, 2018).

Additionally, different fields of investigation already used VD to understand interactions between elements of a system producing *functional effects* (synergies). In the next section, we present a brief summary of some of such studies. Thus, supporting our claim that quantitative methods based on Voronoi diagrams can be an effective strategy to capture purposeful spatial interactions in high-performance football, with a *glocal* metric-topological approach (Kouzoubov and Austin, 2004; Tomatis, Nourbakhsh, and Siegwart, 2003).

## 3.4 Using Voronoi diagrams (VD) to assess physical and social interactions

In the most varied fields of investigation, regardless of the considered scale, there are examples of assessment methods combining different metrics computed from Voronoi diagrams (VD). In physics, Lazar and colleagues (2015) demonstrated how the Voronoi cell's topology can be used to classify the local structure of particles in ordered and disordered systems. By capturing structural information about the local neighbourhood of each particle with Voronoi diagrams, it was possible to understand the behaviour of physical systems and explore how a crystalline structure can be compromised by changes in environmental constraints, e.g. high-temperature (Lazar, Han, and Srolovitz, 2015). These authors argued that the "topological type of each Voronoi cell provides a robust structural description of the local neighbourhood of a particle" and that the "distribution of topological types in a system can be interpreted as a statistical-topological description of the system as a whole" (Lazar, Han, and Srolovitz, 2015, p5777-5778).

In molecular and cellular biology, VD has been used "for the analysis of the interactions between chains in a protein, the interactions between proteins and the interactions between any sets of atomic structures"

(C. M. Kim et al., 2006, p1203). But also to describe the neighbourhood of the molecules and perform single-molecule localization microscopy cluster analysis (with diverse applications in the health area as described by Khater and colleagues, 2020), to understand rigidity in a broad class of models of dense biological tissues (Sussman and Merkel, 2018) or to assess how a global topological order emerges through the local mechanical control of cell divisions (Jackson et al., 2019). Voronoi tessellations methods are an option to study the macro level of the forest dynamics (Mercier and Baujard, 1997), such as the topographical changes of forest structure (Muvengwi et al., 2018), where VD “represents one of the best solutions to determine neighbouring competitors of a tree” (Palaghianu, 2016, p1).
But if the interactions between trees are relatively static, the use of VD to understand fish schools or flocks of birds is more dynamic. In this realm, VD were used to improve the self-propelled particle (SPP) models (Tams Vicsek et al., 1995; Czirók, Barabási, and Tamás Vicsek, 1999; Grégoire, Chaté, and Tu, 2003; Grégoire and Chaté, 2004). In this case, VD were used to capture the collective motion of different animal species by the analysis of the layers of the Voronoi neighbours around each element (Ballerini et al., 2008; Rahmani, Peruani, and Romanczuk, 2020). The SPP models based on VD to study animal synergies progressively improved (Ginelli and Chaté, 2010; Faria et al., 2010; Camperi et al., 2012).

### 3.4.1 Voronoi diagrams to assess human interpersonal interactions

To understand people’s motion in video sequences, Jacques and colleagues (2007) proposed a model to recognize individual and group information through video images, using sequences of VD to assess crowds’ behaviour. Equally, VD were used to build algorithms to automatically detect important events from video images (e.g., a crowd running away) or to capture possible patterns from human movement (e.g., the patterns when entering or exiting a building) (Soldera et al., 2015; Amores and Vasardani, 2018). In the works of Jacques and colleagues (2007) and Soldera and colleagues (2015), the geometry of Voronoi polygons was “explored to extract and quantify sociological and psychological individual characteristics, which are used to detect the possible kinds of interactions proposed by Hall” (Jacques et al., 2007, p322). Such interactions were analysed, using as reference the work of Hall from 1959 (The Silent Language, Doubleday Company) to detect group formations and to assess people’s personal space (PS), defined as an “area with invisible boundaries surrounding an individual’s body” (Jacques et al., 2007, p321). These approaches had the merit of linking perception with the space around each individual during personal interactions, using the reference of Gold (C. M. Gold, 1992, p220) that the “Voronoi model may indeed relate to visual perception and the concept of neighbour”.Gold and his works were influential in the techniques commonly used at the level of the geographic information system (GIS) and the advantages of VD connecting GIS with visual perception (C. M. Gold, 1992; C. Gold, 1995).
Gold’s argument is based on manual cartographic operations and how humans manipulate space in operations like “drawing a line on a partially completed map” where a “small number of nearby objects on the map […] are sufficient to make local decisions about where to draw the line or where not to - either to make a contact or to avoid one”, confirming that the “visual estimation of the relative contribution of neighbouring data points is not based on metric decisions, but on the relative positions of the ”neighbouring”

data points (in a Voronoi sense)" (C. M. Gold, 1992, p226). VD is also appropriate to assess macroscopic human interactions. For example, to study public health problems such as suicides on the Austrian railway network and its proximity to psychiatric institutions (Strauss et al., 2017), or the spatial distribution of crime in the city of St. Louis using networks Voronoi (Meyer, 2010), or even spatial interactions among people to detect dengue fever clusters in a southeast Brazilian town (Duczmal et al., 2011). Within the highly competitive business environment, the topological properties of networks emerging from the evolving patterns captured by two-dimensional Voronoi diagrams can lead to "evolving patterns when the interaction between the agents is local" (Szeto, 2007, p96).

### 3.4.2 Using Voronoi diagrams to program the interactions of autonomous robots

The use of Voronoi diagrams (VD) arrived in the field of robotics. Especially in the field of the behaviour-based robotics (Steels and Brooks, 2018), where algorithms establish a "coupled link between action and perception to enable intelligent behaviour", and "real robots show that a coupling of action and perception systems is beneficial when having to interact with the world" (Green and Heekeren, 2009, p209). The use of Voronoi regions to detect the "available space" (Lindhé, Ögren, and Johansson, 2005, p1790) or "space dominance" for each autonomous agent and provide the emergence of a self-coordinated movement of a group of vehicles, where "stable and collision-free flocking in environments with complex obstacles" (T. Vicsek, 2008, p8) could take place.

In fact, the commonly designated as self-propelled particles (SPP) models, that seek to capture the principles that govern the coordination of the individuals' movements during collective behaviour (Reynolds, 1987; Ballerini et al., 2008; Hasson and Frith, 2016), have offered the basis for algorithms to coordinate multi-vehicle systems. This flocking approach to autonomous vehicles was inspired by the principles for social behaviour in animals (Kouzoubov and Austin, 2004; Tomatis, Nourbakhsh, and Siegwart, 2003), using VD (Stergiopoulos and Tzes, 2011; Konolige, Marder-Eppstein, and Marthi, 2011; Hou, Yuan, and Schwertfeger, 2019). These studies were based on the idea that VD can allow a robot to "navigate in an a priori unknown and non-specific large scale environment" (Van Zwynsvoorde, Simeon, and Alami, 2000, p897), and to coordinate the displacements of a team during a robotic football match (Law, 2005).

## 3.5 How Voronoi diagrams can be used to assess football team's synergies?

From an ecological dynamics framework (Duarte Araújo, Keith Davids, and Hristovski, 2006), behaviour is mainly explained by synergetic properties (Kelso, 2022) also at a team level (D. Araújo and K. Davids, 2016). In this paper, we argue that Voronoi diagrams and related compound variables (as exemplified in Figure 3.1), can be used to capture the properties of synergies in football teams, fulfilling some previous limitations. In the next section, we discuss how VD can be used to understand the *intentionality* in the emergence of group behaviour from players' interactions. For this end, we discuss the four team's synergy properties proposed by Araújo and Davids (2016) - interpersonal linkages, dimensional compression, reciprocal compensation, degeneracy – which are expressed when players act collectively on a *shared affordance*.

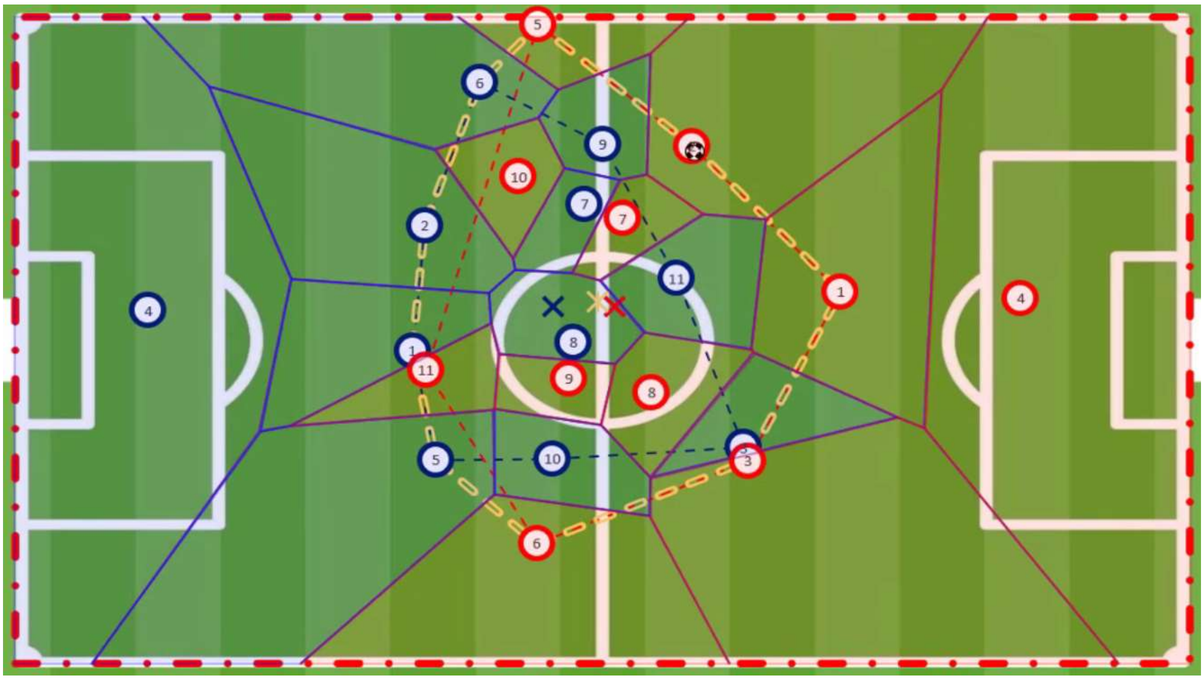


**Figure 3.1:** One-time frame Voronoi diagram.
*Example of Voronoi diagram (VD) with players' Voronoi cells (red and blue polygons), in a match frame. Compound variables can be extracted from the VD and other metrics, e.g., match and teams' centroids (yellow, blue and red crosses) or the match (dashed yellow polygon) and team's convex hull (dashed red polygon for the in possession and dashed blue polygon for the out of possession team).*

### 3.5.1 The assessment of sport team's interpersonal linkages by Voronoi Diagrams

In a Voronoi diagram (VD), from a given instant of a football match, all players' positions are necessary to compute the portion of space that is near to each player than from any other player on the pitch (S. Kim, 2004). Consequently, a VD is a method of dividing the pitch space by all 22 players, attributing to each player a "sphere of influence" (Taki and J. i. Hasegawa, 2000), "dominant region" (Taki and J.-i. Hasegawa, 2000) or "*space dominance*" (Efthimiou, 2021). Each individual "space dominance" is directly related to the "division of labour" (Corning, 2010) that results from players' coordinated displacements on the pitch. In a given instant, a single player alone cannot dominate all the pitch, and the way a team as a whole can dominate more extensive regions of the game space is through their elements' synergistic cooperation (dividing the space by their players). Therefore, when the pitch area is divided by all players into a single VD, becomes possible to capture the spatio-temporal patterns of the team's "division of labour" or "interpersonal linkages", a synergies' property that refers to "the specific contribution of each element to a group task" (D. Araújo and K. Davids, 2016, p8), for example, to maintain the ball possession or to progress towards the opponent's goal aiming to score.
Despite its limitations (Efthimiou, 2021), the usefulness of VD to assess the division of space, as part

of the players' interpersonal linkages, in the context of team sports was already addressed in several studies (S. Kim, 2004; Gazimba, Ricardo Duarte, and Duarte Araújo, 2011; Santana, 2011; Fonseca et al., 2012; Ueda, Masaaki, and Hiroyuki, 2014; António Lopes et al., 2015; Perl and Memmert, 2016; Robert Rein, Raabe, and Memmert, 2017a; Maymin, 2019). However, to understand the division of the playing space at a given time, it is important to consider "the central notion of opposition [that] leads us to consider the two teams as interacting organised systems" (Gréhaigne, Bouthier, and David, 1997, p145). Consequently, we argue that the understanding of the division of field space should not be considered only among colleagues from the same team (as done by Santana, 2011), but from the totality of players on the pitch, including those from the opposing team (António Lopes et al., 2015). This approach can contribute to the assessment of the spatial opportunities perceived by all players (Mcguckian et al., 2017).

### 3.5.2 The assessment of dimensional compression by Voronoi Diagrams

Voronoi diagrams (VD) can be used in physics "in contrast to conventional order parameters – which are typically useful for studying either ordered or disordered systems, but not both" (Lazar, Han, and Srolovitz, 2015, p5769). To Lazar and colleagues (2015), VD are a valid alternative to reduce the many degrees of freedom of all kinds of systems, dimensionally compressing the information from a hybrid metric-topological point of view. A VD each cell has been seen as a "personal space" (Soldera et al., 2015) which implies that it expresses intentionality, as it happens when acting on an affordance (C. Gold, 1995). In a game landscape (Gómez-Jordana et al., 2019), VC can capture players' affordances of the match, for example, related to the "empty space" (Baddeley and Gill, 1994). These affordances are perceived by each player, but also by other players on the field (Passos, Cordovil, et al., 2012; Pedro Silva et al., 2013; D. Araújo, P. Silva, and J. Ramos, 2014), constraining players' actions.

VD can quantify the spaces perceived to act (e.g., to receive the ball, dribble, pass or shoot). This quantification expresses players' decision-making of who is the player that is nearer to the ball and could act upon it. In fact, a player can act upon the ball if it is within its own VC or in a near future, as it is implied in the notion of affordance. Therefore, as people during the passage of a narrow corridor (Jacques et al., 2007; Soldera et al., 2015), players are constantly perceiving spaces from a functional perspective, e.g., if they are the player of their team closest to the ball or which teammate is best positioned to score (affordance to pass).

The division of the total space of the playing field by all the elements present on it can inform about the dimensional compression of a team synergy, i.e., "the degrees of freedom that potentially are independent become coupled so that the synergy has fewer degrees of freedom (a lower dimensionality) than the set of components from which it arises" (D. Araújo and K. Davids, 2016, p7). Thus, VD metrics can constitute a kind of eco-physical variable (Duarte Araújo, Keith Davids, and Hristovski, 2006; Menuchi et al., 2018), because the "Voronoi model may indeed relate to visual perception and the concept of neighbour" (C. M. Gold, 1992, p220). Just as the global centroid of a team is the result of the players' positions, which can be grouped at different zooms (Merlin et al., 2020), also individual areas of Voronoi cells can constrain teams' degrees of freedom showing dimensional compression, "by measuring the total area of all Voronoi cells from each team, it is possible to obtain a dominant ratio of one team over the other" (D. Araújo and K. Davids, 2016, p8).

Sports sciences research has shown that VD is a promising metric to dimensionally compress teams' collective behaviours (S. Kim, 2004; Fonseca et al., 2012; A. Lopes et al., 2013; Ueda, Masaaki, and Hiroyuki, 2014; António Lopes et al., 2015). Even if the "implicit assumption of the standard VD is that all players are equally fast, start from a static position, and can infinitively accelerate [are] unrealistic assumptions" (Robert Rein, Raabe, and Memmert, 2017b, p179), none of the currently proposed models which try to include speeds and trajectories to relativize the calculation of the "space dominance" of each player, can effectively integrate all the complexity of the football game. With the conviction that "Euclidean distance to construct individual player's cells are appropriate" (Robert Rein, Raabe, and Memmert, 2017b, p179), besides their limitations and sources of error (Horton et al., 2017), "VD can then be considered to measure individual and team dominant regions" (Fonseca et al., 2012, p1958), indicating the dominance of one team over the other, i.e., "the proportion of space owned by a team" (Spencer, Hawkey, and S. Robertson, 2019, p1777). However, at the high-level football context this is a subject that needs to be further researched.

### 3.5.3 The assessment of reciprocal compensation through Voronoi Diagrams

The reciprocal compensation assessment by means of Voronoi diagrams (VD), can be extracted from players' interactions. This means that a team can manage their *functional degrees of freedom* (fDOF) as a whole. fDOF can be defined as the "remaining DOF that are allowed to independently vary during a movement task due to the imposition of m task-specific constraints on the original n DOF" (Li, 2006, p303). Teams can be seen as coordinative structures (A. Williams, K. Davids, and J. Williams, 1999) that, by forming synergies manage the abundance of their fDOF, something already seen at the interpersonal level (Riley et al., 2011; D. Araújo and K. Davids, 2016).

Match constraints, at the level of the task, environment and organism (Newell, 1986), channel the players' perception of affordances during their actions, in a cyclical process of acting to perceive and perceive to act (Travassos and Duarte Araújo, 2010; D. Araújo, P. Silva, and J. Ramos, 2014; Duarte Araújo, Hristovski, et al., 2019; Dicks, Duarte Araújo, and Kamp, 2019). In team sports, the "ability to see an opening for a pass" (Gudmundsson and Wolle, 2014, p17) or a pass affordance is perceptually based (A. Ramos et al., 2020), and constrained by players' characteristics and states such as distance, speed and angles (Passos, Cordovil, et al., 2012; Travassos, Ricardo Duarte, et al., 2012; Corrêa et al., 2014), in an evolving context where gaps are constantly opening and closing (Horton et al., 2017). However, the circular causality (Pol et al., 2020) that is present in all synergies (Marsh et al., 2006), implies not only the local constraints but also the global team tactical configuration which constrains players' interactions (Ribeiro, Keith Davids, et al., 2019).

Despite the existing methods to capture players' dispersion on the field and correspondent group tactical behaviours (D. Araújo, P. Silva, and K. Davids, 2015; Ric et al., 2016; López-Felip et al., 2018; Marcelino et al., 2020), assessing the global team configuration, can be supported by a hybrid metric-topological

map (Simhon and Dudek, 1998; Tomatis, Nourbakhsh, and Siegwart, 2003; Kouzoubov and Austin, 2004; Konolige, Marder-Eppstein, and Marthi, 2011; Shang and Bouffanais, 2014) that use Voronoi diagrams (VD) to capture, at every instant, the relative position of all players (in relation to the goalposts and the ball). This 'relative position' is what in ecological dynamics is designated eco-physical variables, which contextualise and define the purpose of every action (Duarte Araújo, Keith Davids, and Hristovski, 2006). Based on the self-propelled particle (SPP) models (Tams Vicsek et al., 1995; Czirók, Barabási, and Tamás Vicsek, 1999; Grégoire, Chaté, and Tu, 2003; Grégoire and Chaté, 2004), VD can be used to assess the whole team behaviour, capturing synergies' reciprocal compensation.
The SPP methods, which are an adequate method to capture, for example, the dynamics of fish schools (Reuter and Breckling, 1994), flocks of birds (Couzin et al., 2002), and human crowds behaviours, as during "Mexican waves" (Farkas, D. Helbing, and T. Vicsek, 2002) or in the formation of traffic jams (Dirk Helbing and Huberman, 1998), were used to identify behaviours where "synchronization and swarming occur together" (O'Keeffe, Hong, and Strogatz, 2017, p1). As in other complex systems (Jeffrey, 1990; Parrott, 2010), players do not randomly disperse in the field of play but act in a coordinated way (Duarte and Frias, 2011) around attractors (Gorman et al., 2017). This turns possible to adapt SPP models, namely the ones using VD (Ginelli and Chaté, 2010), to assess teams' "flocking" (Lindhé, Ögren, and Johansson, 2005) configurations and their reciprocal compensations.

### 3.5.4 The assessment of degeneracy through Voronoi Diagrams

"Degeneracy and multifunctionality are ubiquitous in living things" (Kelso, 2022, p3). As defined by Edelman and Gally (2001, p13763), degeneracy is "the ability of elements that are structurally different to perform the same function or yield the same output". Even if a Voronoi diagram (VD) globally divides the space for all players on the pitch, it enables a closer zoom-in for more local contexts. This "*glocal*" use of VD allow the assessment of players' space in the zone closer to the ball, for example, to understand the players' decision-making about who is ready to shoot to the opponent's goal. In this example, degeneracy means that the ball carrier can perform the finishing function himself (if he decides to shoot) but can also perceive affordances to pass to a teammate who might be better positioned to do so. This illustrates teams' degeneracy and multifunctionality. Therefore, to understand the shooting situations, concepts like the attacking "dangerousity" (Link, Lang, and Seidenschwarz, 2016) or the "Expected Possession Value" (Fernández, Bornn, and Cervone, 2019), underlined the importance of evaluate players' spaces to understand their decisions.
If a given function (e.g., shot at the opponent's goal) can be performed by different players, which basically corresponds to a degenerating property of the team as a whole, the ball carrier will choose to shoot when he/she perceives he can achieve the goal. If, absurdly, there was only one player who could shoot at the opponent's goal, then it would become predictable and easily nullified by the opponent. But on the other hand, not all players can find themselves in a position to shoot at the goal. This is why, for the different functions implied in a match, successful teams develop the right balance between stability and flexibility, that is, a given level of degeneracy (Immler et al., 2021). Thus, from our point of view, a method grounded

in VD can quantify the degeneracy of team synergies. Especially if it can assess players' degenerate choices about who can perform a given function (e.g., shoot at goal).

## 3.6 Conclusion

This article supports the perspective that Voronoi diagrams can be used to develop methods to assess the functional effects emerging from players' interactions. These functional effects are the result of collective synergies that support the team's performance (Corning, 2018), and that exhibit the properties of interpersonal linkages, dimensional compression, reciprocal compensation and degeneracy (D. Araújo and K. Davids, 2016). In a football game, players perceive affordances (Gibson, 1979) to (inter)act with others, creating soft-assembled synergies to achieve task goals (Withagen et al., 2012). Due to the circular causality (Pol et al., 2020), from these team synergies will emerge new spatial configurations that result in new affordances to explore and, consequently, renewed synergies (Plumert and Kearney, 2018). We argue therefore that important synergies' properties can be extracted from matches positional data to test if players' "space dominance" (Efthimiou, 2021) can be linked with a set of team functions in a match (e.g., creating scoring opportunities, maintain ball possession or achieve a certain territorial dominance). Using this ecological dynamics approach, Voronoi diagrams can be used to explain football teams' performance. The idea is that assessing the distribution of players by the pitch space over time, can be possible to capture teams' synergies' properties that support teams' performance (D. Araújo and K. Davids, 2016).

Using Voronoi diagrams-based tools to measure the various properties of synergies at the level of football teams, also reduce the gap between research and coaches' practice. The great potential of Voronoi diagrams, despite all their limitations (Efthimiou, 2021), is their simplicity (C. Gold, 1995), being easily perceived by practitioners, players and technical staff of high-performance teams. We suggest by assessing the properties of collective synergies, VD can constitute an important tool for match analysis and in the support for the design of representative training tasks, especially in high-level teams where positional data is highly available.

### Abbreviations

DT - Delauney triangulations

VC - Voronoi cell

VD - Voronoi diagram

SPP - Self-Propelled Particle

fDOF - functional Degrees of Freedom

## References


Amores, David and Maria Vasardani (2018). "Movement pattern analysis using Voronoi Diagrams". In: *Research@ Locate*, pp. 41–48.

Araújo, D. and K. Davids (2016). "Team synergies in sport: Theory and measures". In: *Frontiers in Psychology* 7.SEP, pp. 1–13. DOI: 10.3389/fpsyg.2016.01449Team.

Araújo, D., P. Silva, and K. Davids (2015). "Capturing group tactical behaviors in expert team players." In: *Routlegde Handbook of Sport Expertise*. Ed. by Daniel Baker and Damian Farrow. New York: Routledge, pp. 209–220.

Araújo, D., P. Silva, and J. Ramos (2014). "Affordance-based decisions guide team synergies during match performance". In: *Research in Physical Education, Sport and Health* 3.1, pp. 19–26.

Araújo, Duarte, Keith Davids, and Robert Hristovski (2006). "The ecological dynamics of decision making in sport". In: *Psychology of Sport and Exercise* 7.6, pp. 653–676. DOI: 10.1016/j.psychsport.2006.07.002.

Araújo, Duarte, Robert Hristovski, et al. (2019). "Ecological cognition: expert decision-making behaviour in sport". In: *International Review of Sport and Exercise Psychology* 12.1, pp. 1–25. DOI: 10.1080/1750984X.2017.1349826.

Baddeley, A. and R. Gill (1994). *The empty space hazard of a spatial pattern*. University of Western Australia. Department of Mathematics.

Ballerini, M. et al. (2008). "Interaction ruling animal collective behavior depends on topological rather than metric distance: Evidence from a field study". In: *Proceedings of the National Academy of Sciences of the United States of America* 105.4, pp. 1232–1237. DOI: 10.1073/pnas.0711437105.

Boots, Barry and Arthur Getis (2020). *Point Pattern Analysis. Web Book of Regional Science. Regional Research Institute, West Virginia University. Edited by Grant Ian Thrall, 1986; Randall Jackson, 2020*.

Bradley, PS and JD Ade (2018). "Are Current Physical Match Performance Metrics in Elite Soccer Fit for Purpose or is the Adoption of an Integrated Approach Needed?" In: *International Journal of Sports Physiology and Performance* 13.5, pp. 656–664.

Caldeira, Nelson (2013). *Futebol glocal*. Funchal, Portugal: Sports Science, Ida.

Camperi, Marcelo et al. (2012). "Spatially balanced topological interaction grants optimal cohesion in flocking models". In: *Interface Focus* 2.6, pp. 715–725. DOI: 10.1098/rsfs.2012.0026.

Carling, Christopher (2013). "Interpreting physical performance in professional soccer match-play: Should we be more pragmatic in our approach?" In: *Sports Medicine* 43.8, pp. 655–663. DOI: 10.1007/s40279-013-0055-8.

Carrilho, Daniel et al. (Sept. 2020). "Using optical tracking system data to measure team synergic behavior: Synchronization of player-ball-goal angles in a football match". In: *Sensors (Switzerland)* 20.17, pp. 1–14. DOI: 10.3390/s20174990.

Chiu, S. N. (2003). "Spatial point pattern analysis by using Voronoi diagrams and Delaunay tessellations - A comparative study". In: *Biometrical Journal* 45.3, pp. 367–376. DOI: 10.1002/bimj.200390018.

Clemente, Filipe Manuel et al. (2015). “Using network metrics in soccer: A macro-analysis”. In: *Journal of Human Kinetics* 45.1, pp. 123–134. DOI: 10.1515/hukin-2015-0013.

Corning, Peter (2010). *Holistic Darwinism*. University of Chicago Press.

— (2018). *Synergistic Selection: How Cooperation Has Shaped Evolution And The Rise Of Humankind*. WORLD SCIENTIFIC PUBLISHING CO PTE LTD.

Corrêa, Umberto Cesar et al. (2014). “Interpersonal Angular Relations between Players Constrain Decision-Making on the Passing Velocity in Futsal”. In: *Advances in Physical Education* 04.02, pp. 93–101. DOI: 10.4236/ape.2014.42013.

Coupe, Tom, Olivier Gergaud, and Abdul Noury (2017). “Biases in Voting - The Case of the FIFA Best Player Award”. In: *Oxford Bulletin of Economics & Statistics* 80.2.

Couzin, Iain D. et al. (2002). “Collective memory and spatial sorting in animal groups”. In: *Journal of Theoretical Biology* 218.1, pp. 1–11. DOI: 10.1006/jtbi.2002.3065.

Czirók, András, Albert László Barabási, and Tamás Vicsek (1999). “Collective motion of self-propelled particles: Kinetic phase transition in one dimension”. In: *Physical Review Letters* 82.1, pp. 209–212. DOI: 10.1103/PhysRevLett.82.209. arXiv: 9712154 [cond-mat].

Davids, Keith, Duarte Araújo, and Rick Shuttleworth (2005). “Applications of Dynamical Systems Theory to Football”. In: *Science and Football V: The Proceedings of the Fifth World Congress on Science and Football* i, pp. 537–550.

Dellal, Alexandre et al. (2011). “Comparison of physical and technical performance in European soccer match-play: Fa Premier League and La Liga”. In: *European Journal of Sport Science* 11.1, pp. 51–59. DOI: 10.1080/17461391.2010.481334.

Dicks, Matt, Duarte Araújo, and John Kamp (2019). “Perception-action for the study of anticipation and decision making”. In: *Anticipation and Decision Making in Sport*. Routledge.

Duarte, R and T Frias (2011). “Collective intelligence: An incursion into the tactical performance of football teams”. In: *Proceedings of the First International Conference in Science and Football*, pp. 15–17.

Duarte, Ricardo (2012). *Interpersonal Coordination Tendencies in Soccer: Uncovering the tactical side of the game*. Lambert.

Duarte, Ricardo, Duarte Araújo, Vanda Correia, et al. (2013). “Competing together: Assessing the dynamics of team-team and player-team synchrony in professional association football”. In: *Human Movement Science* 32.4, pp. 555–566. DOI: 10.1016/j.humov.2013.01.011.

Duarte, Ricardo, Duarte Araújo, Luís Freire, et al. (2012). “Intra- and inter-group coordination patterns reveal collective behaviors of football players near the scoring zone”. In: *Human Movement Science* 31.6, pp. 1639–1651. DOI: 10.1016/j.humov.2012.03.001.

Duczmal, Luiz H. et al. (2011). “Voronoi distance based prospective space-time scans for point data sets: A dengue fever cluster analysis in a southeast Brazilian town”. In: *International Journal of Health Geographics* 10, pp. 1–14. DOI: 10.1186/1476-072X-10-29.

Edelman, G. M. and J. A. Gally (2001). “Degeneracy and complexity in biological systems”. In: *Proceedings of the National Academy of Sciences of the United States of America* 98.24, pp. 13763–13768. DOI: 10.1073/pnas.231499798.

Efthimiou, Costas J. (2021). “The Voronoi Diagram in Soccer: a theoretical study to measure dominance space”. In: *arXiv preprint arXiv:2107.05714.*, pp. 1–32. arXiv: 2107.05714.

Faria, Jolyon J. et al. (2010). “A novel method for investigating the collective behaviour of fish: Introducing 'Robofish'”. In: *Behavioral Ecology and Sociobiology* 64.8, pp. 1211–1218. DOI: 10.1007/s00265-010-0988-y.

Farkas, I., D. Helbing, and T. Vicsek (2002). “Mexican Waves in an Excitable Medium: The Stimulation of this Motion Among Expectant Spectators Is Explained”. In: *Nature* 419, pp. 131–132.

Fernández, Javier, Luke Bornn, and Dan Cervone (2019). “Decomposing the Immeasurable Sport: A deep learning expected possession value framework for soccer”. In: *MIT Sloan Sports Analytics Conference*, pp. 1–18.

Folgado, Hugo et al. (Apr. 2018). “Exploring how movement synchronization is related to match outcome in elite professional football”. In: *Science and Medicine in Football* 2.2, pp. 101–107. DOI: 10.1080/24733938.2018.1431399.

Fonseca, Sofia et al. (2012). “Spatial dynamics of team sports exposed by Voronoi diagrams”. In: *Human Movement Science* 31.6, pp. 1652–1659. DOI: 10.1016/j.humov.2012.04.006.

Frencken, Wouter et al. (2011). “Oscillations of centroid position and surface area of soccer teams in small-sided games”. In: *European Journal of Sport Science* 11.4, pp. 215–223. DOI: 10.1080/17461391.2010.499967.

Gazimba, Vítor, Ricardo Duarte, and Duarte Araújo (2011). “A interacção espácio-temporal dos jogadores e das equipas de futebol captada através dos diagramas de voronoi”. In: *Gymnasium, Revista Educação Física e Desporto*, pp. 139–153.

Gibson, J. (1979). *The ecological approach to visual perception*. Boston: Houghton, Mifflin and Company.

Ginelli, Francesco and Hugues Chaté (2010). “Relevance of metric-free interactions in flocking phenomena”. In: *Physical Review Letters* 105.16, pp. 1–5. DOI: 10.1103/PhysRevLett.105.168103. arXiv: 1007.1783.

Gold, Christopher (1995). “Advantages of the Voronoi spatial model”. In: *Proceedings of Eurocarto XII*. Copenhagen, pp. 1–10.

Gold, Christopher M (1992). “The Meaning of “ Neighbour ””. In: *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space*. Springer, Berlin, Heidelberg, pp. 220–235.

Gómez-Jordana, Luis et al. (2019). “Landscapes of passing opportunities in Football – where they are and for how long are available ?” In: *Barça Sports Analytics Summit-2nd edition At: Camp Nou- Barcelona*. November, pp. 1–14.

Gonçalves, Bruno et al. (2017). “Exploring team passing networks and player movement dynamics in youth association football”. In: *PLoS ONE* 12.1, pp. 1–13. DOI: 10.1371/journal.pone.0171156.

Gorman, Jamie C. et al. (2017). “Understanding and modeling teams as dynamical systems”. In: *Frontiers in Psychology* 8.JUL, pp. 1–18. DOI: 10.3389/fpsyg.2017.01053.

Green, Nikos and Hauke R. Heekeren (2009). *Perceptual decision making: a bidirectional link between mind and motion*. DOI: 10.1016/S0079-6123(09)01317-X.

Grégoire, Guillaume and Hugues Chaté (2004). “Onset of Collective and Cohesive Motion”. In: *Physical Review Letters* 92.2, p. 4. DOI: 10.1103/PhysRevLett.92.025702. arXiv: 0401208 [cond-mat].

Grégoire, Guillaume, Hugues Chaté, and Yuhai Tu (2003). “Moving and staying together without a leader”. In: *Physica D: Nonlinear Phenomena* 181.3-4, pp. 157–170. DOI: 10.1016/S0167-2789(03)00102-7. arXiv: 0401257 [cond-mat].

Gréhaigne, Jean Francis, Daniel Bouthier, and Bernard David (1997). “Dynamic-system analysis of opponent relationships in collective actions in soccer”. In: *Journal of Sports Sciences* 15.2, pp. 137–149. DOI: 10.1080/026404197367416.

Gudmundsson, Joachim and Thomas Wolle (2014). “Football analysis using spatio-temporal tools”. In: *Computers, Environment and Urban Systems* 47, pp. 16–27. DOI: 10.1016/j.compenvurbsys.2013.09.004.

Hasson, Uri and Chris D. Frith (2016). “Mirroring and beyond: Coupled dynamics as a generalized framework for modelling social interactions”. In: *Philosophical Transactions of the Royal Society B: Biological Sciences* 371.1693. DOI: 10.1098/rstb.2015.0366.

Headrick, Jonathon et al. (2012). “Proximity-to-goal as a constraint on patterns of behaviour in attacker–defender dyads in team games”. In: *Journal of Sports Sciences* 30.3, pp. 247–253. DOI: 10.1080/02640414.2011.640706.

Helbing, Dirk and Bernardo A. Huberman (1998). “Coherent Moving States in Highway Traffic”. In: *Nature* 396.6713, pp. 738–740. DOI: 10.1038/25499. arXiv: 9805025 [cond-mat].

Herold, Mat et al. (2021). “Attacking key performance indicators in soccer: Current practice and perceptions from the elite to youth academy level”. In: *Journal of Sports Science and Medicine* 20.1, pp. 158–169. DOI: 10.52082/jssm.2021.158.

Horton, Michael et al. (2017). “Classification of passes in football matches using spatiotemporal data”. In: *ACM Transactions on Spatial Algorithms and Systems* 3.2. DOI: 10.1145/3105576. arXiv: 1407.5093.

Hou, Jiawei, Yijun Yuan, and Soren Schwertfeger (2019). “Area graph: Generation of topological maps using the voronoi diagram”. In: *2019 19th International Conference on Advanced Robotics, ICAR 2019* Vd, pp. 509–515. DOI: 10.1109/ICAR46387.2019.8981588. arXiv: 1910.01019.

Hughes, Mike and Roger Bartlett (2002). “The use of performance indicators in performance analysis”. In: *Journal of Sports Sciences* 20, pp. 739–754. DOI: 10.4324/9780429340130-6.

Immler, Sebastian et al. (2021). “Guardiola, Klopp, and Pochettino: The Purveyors of What? The Use of Passing Network Analysis to Identify and Compare Coaching Styles in Professional Football”. In: *Frontiers in Sports and Active Living* 3.October, pp. 1–9. DOI: 10.3389/fspor.2021.725554.

Jackson, Matthew D.B. et al. (2019). “Global Topological Order Emerges through Local Mechanical Control of Cell Divisions in the Arabidopsis Shoot Apical Meristem”. In: *Cell Systems* 8.1, 53–65.e3. DOI: 10.1016/j.cels.2018.12.009.

Jacques, Julio Cezar Silveira et al. (2007). “Understanding people motion in video sequences using Voronoi diagrams: Detecting and classifying groups”. In: *Pattern Analysis and Applications* 10.4, pp. 321–332. DOI: 10.1007/s10044-007-0070-1.

Jeffrey, H Joel (1990). *Chaos game representation of gene structure*. Tech. rep. 8, p. 2163.

Kelso, J. A.Scott (2022). “On the coordination dynamics of (animate) moving bodies”. In: *Journal of Physics: Complexity* 3.3, pp. 1–16. DOI: 10.1088/2632-072X/ac7caf.

Khater, Ismail M., Ivan Robert Nabi, and Ghassan Hamarneh (June 2020). “A Review of Super-Resolution Single-Molecule Localization Microscopy Cluster Analysis and Quantification Methods”. In: *Patterns* 1.3, p. 100038. DOI: 10.1016/j.patter.2020.100038.

Kim, Chong Min et al. (2006). “Interaction interfaces in proteins via the Voronoi diagram of atoms”. In: *CAD Computer Aided Design* 38.11, pp. 1192–1204. DOI: 10.1016/j.cad.2006.07.007.

Kim, S. (2004). “Voronoi Analysis of a Soccer Game”. In: *Nonlinear Analysis: Modelling and Control* 9.3, pp. 233–240.

Kirk, David and Ann MacPhail (2002). “Teaching Games for Understanding and situated learning: Rethinking the Bunker-Thorpe model”. In: *Journal of Teaching in Physical Education* 21.2, pp. 177–192. DOI: 10.1123/jtpe.21.2.177.

Konolige, Kurt, Eitan Marder-Eppstein, and Bhaskara Marthi (2011). “Navigation in hybrid metric-topological maps”. In: *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 3041–3047. DOI: 10.1109/ICRA.2011.5980074.

Kouzoubov, Kirill and David Austin (2004). “Hybrid Topological / Metric Approach to SLAM”. In: *IEEE International Conference on Robotics and Automation, 2004. Proceedings*, pp. 872–877.

Latash, M. (2008). *Synergy*. New York and Oxford: University Press.

Law, James (2005). “Analysis of Multi-Robot Cooperation using Voronoi Diagrams”. In: *3rd International RCL/VNIItransmash Workshop on Planetary Rovers, Space Robotics and Earth-Based Robots*, p. 6.

Lazar, Emanuel A., Jian Han, and David J. Srolovitz (2015). “Topological framework for local structure analysis in condensed matter”. In: *Proceedings of the National Academy of Sciences of the United States of America* 112.43, E5769–E5776. DOI: 10.1073/pnas.1505788112. arXiv: 1508.05937.

Li, Zong-Ming (2006). “Functional Degrees of Freedom”. In: *Motor Control* 10, pp. 301–310.

Lindhé, Magnus, Fetter Ögren, and Karl Henrik Johansson (2005). “Flocking with obstacle avoidance: A new distributed coordination algorithm based on Voronoi partitions”. In: *Proceedings - IEEE International Conference on Robotics and Automation* 2005, pp. 1785–1790. DOI: 10.1109/ROBOT.2005.1570372.

Link, Daniel, Steffen Lang, and Philipp Seidenschwarz (2016). “Real time quantification of dangerousity in football using spatiotemporal tracking data”. In: *PLoS ONE* 11.12, pp. 1–16. DOI: 10.1371/journal.pone.0168768.

Lopes, A. et al. (2013). “Tracking Multiple Handball Players using Multi-Commodity Network Flow for Assessing Tactical Behavior”. In: *Scientific Conference Women and Handball: Scientific and Practical Approaches*.

Lopes, António et al. (2015). “Using Voronoi diagrams to describe tactical behaviour in invasive team sports: An application in basketball”. In: *Cuadernos de Psicologia del Deporte* 15.1, pp. 123–130. DOI: 10.4321/S1578-84232015000100012.

López-Felip, Maurici A. et al. (2018). “A cluster phase analysis for collective behavior in team sports”. In: *Human Movement Science* 59.March, pp. 96–111. DOI: 10.1016/j.humov.2018.03.013.

Marcelino, Rui et al. (2020). “Collective movement analysis reveals coordination tactics of team players in football matches”. In: *Chaos, Solitons and Fractals* 138. DOI: 10.1016/j.chaos.2020.109831.

Marsh, Kerry L. et al. (2006). "Contrasting approaches to perceiving and acting with others". In: *Ecological Psychology* 18.1, pp. 1–38. DOI: 10.1207/s15326969eco1801_1.

Mateus, J. (2005). "In pursuit of an ecological and fractal approach to soccer coaching". In: *Science and Football V : The Proceedings of the Fifth World Congress on Science and Football,* pp. 561–573.

Maymin, Philip (2019). *SpeedVision: Maximum-Speed-Weighted Voronoi Diagrams for the NFL*. Tech. rep. University of Bridgeport, Bridgeport, CT.

Mcguckian, Thomas et al. (2017). "The Impact of Constraints on Visual Exploratory Behavior in Football". In: *Studies in Perception & Action XIV* July, pp. 85–87.

McLean, Scott et al. (2018). "The effect of playing formation on the passing network characteristics of a professional football team". In: *Human Movement* 2018.5, pp. 14–22. DOI: 10.5114/hm.2018.79416.

Menuchi, Marcos R.T.P. et al. (2018). "Effects of spatiotemporal constraints and age on the interactions of soccer players when competing for ball possession". In: *Journal of Sports Science and Medicine* 17.3, pp. 379–391.

Mercier, F and O Baujard (1997). "Voronoi diagrams to model forest dynamics in French Guiana". In: *Proceedings of Geocomputation* 1978, pp. 161–171.

Merlin, Murilo et al. (2020). "Exploring the determinants of success in different clusters of ball possession sequences in soccer". In: *Research in Sports Medicine* 28.3, pp. 339–350. DOI: 10.1080/15438627.2020.1716228.

Meyer, W. (2010). "Analyzing crime on street networks: A comparison of network and Euclidean Voronoi methods." PhD thesis. University of Illinois at Urbana-Champaign, p. 55.

Moura, Felipe Arruda et al. (2012). "Quantitative analysis of Brazilian football players' organisation on the pitch". In: *Sports Biomechanics* 11.1, pp. 85–96. DOI: 10.1080/14763141.2011.637123.

Muvengwi, Justice et al. (Feb. 2018). "Population structure and spatial point-pattern analysis of a mono stand of Acacia polyacantha along a catena in a savanna ecosystem". In: *Forest Ecology and Management* 409, pp. 499–508. DOI: 10.1016/j.foreco.2017.11.056.

Narizuka, T. and Y. Yamazaki (2018). "Characterization of the formation structure in team sports". In: *arXiv preprint*, arXiv:1802.06766.

Newell, K. (1986). "Constraints on the development of coordination". In: *Motor development in children. Aspects of coordination and control*. Ed. by MG Wade and HTA Whiting. Dordrecht: Martinus Nijhoff, pp. 341–360.

O'Keeffe, Kevin P., Hyunsuk Hong, and Steven H. Strogatz (2017). "Oscillators that sync and swarm". In: *Nature Communications* 8.1, pp. 1–12. DOI: 10.1038/s41467-017-01190-3. arXiv: 1701.05670.

Okabe, A., B. Boots, and K. Sugiharam (2000). *Spatial Tessellations: Concepts and Applications of Voronoi Diagrams*. (2nd editi. Wiley.

Palaghianu, C. (2016). "Individual area and spatial distribution of saplings". In: *arXiv preprint arXiv:1602.04006.*

Parrott, Lael (2010). "Measuring ecological complexity". In: *Ecological Indicators* 10.6, pp. 1069–1076. DOI: 10.1016/j.ecolind.2010.03.014.

Passos, Pedro, Duarte Araújo, and Keith Davids (2016). “Competitiveness and the process of co-adaptation in team sport performance”. In: *Frontiers in Psychology* 7.OCT, pp. 1–5. DOI: 10.3389/fpsyg.2016.01562.

Passos, Pedro, Duarte Araújo, Keith Davids, et al. (2009). “Interpersonal pattern dynamics and adaptive behavior in multiagent neurobiological systems: Conceptual model and data”. In: *Journal of Motor Behavior* 41.5, pp. 445–459. DOI: 10.3200/35-08-061.

Passos, Pedro, Rita Cordovil, et al. (2012). “Perceiving affordances in rugby union”. In: *Journal of Sports Sciences* 30.11, pp. 1175–1182. DOI: 10.1080/02640414.2012.695082.

Passos, Pedro, Keith Davids, et al. (2011). “Networks as a novel tool for studying team ball sports as complex social systems”. In: *Journal of Science and Medicine in Sport* 14.2, pp. 170–176. DOI: 10.1016/j.jsams.2010.10.459.

Paul, DJ, PS Bradley, and GP Nassis (2015). “Factors Impacting Match Running Performances of Elite Soccer Players : Shedding Some Light on the Complexity”. In: *International journal of sports physiology and performance* 10.4, pp. 516–519. DOI: doi.org/10.1123/IJSPP.2015-0029.

Perl, Jürgen and Daniel Memmert (2016). “Soccer analyses by means of artificial neural networks, automatic pass recognition and voronoi-cells: An approach of measuring tactical success”. In: *Advances in Intelligent Systems and Computing*. Vol. 392. Springer Verlag, pp. 77–84. DOI: 10.1007/978-3-319-24560-7_10.

Plumert, J. and J. Kearney (2018). “Timing is almost everything: How children perceive and act on dynamic affordances”. In: *Advances in child development and behavior* 55, pp. 173–204. DOI: 10.1016/j.neuron.2015.02.042.Neuromechanical.

Pol, Rafel et al. (2020). “Training or Synergizing? Complex Systems Principles Change the Understanding of Sport Processes”. In: *Sports Medicine - Open* 6.1. DOI: 10.1186/s40798-020-00256-9.

Rahmani, Parisa, Fernando Peruani, and Pawel Romanczuk (2020). “Flocking in complex environments—Attention trade-offs in collective information processing”. In: *PLoS Computational Biology* 16.4, pp. 1–18. DOI: 10.1371/journal.pcbi.1007697. arXiv: 1907.11691.

Ramos, Ana et al. (2020). “The constraint-led approach to enhancing team synergies in sport - What do we currently know and how can we move forward? A systematic review and meta-analyses”. In: *Psychology of Sport and Exercise* 50.May. DOI: 10.1016/j.psychsport.2020.101754.

Ramos, João, Rui J. Lopes, and Duarte Araújo (Jan. 2018). “What’s Next in Complex Networks? Capturing the Concept of Attacking Play in Invasive Team Sports”. In: *Sports Medicine* 48.1, pp. 17–28. DOI: 10.1007/s40279-017-0786-z.

Ramos, João, Rui J. Lopes, Pedro Marques, et al. (2017). “Hypernetworks reveal compound variables that capture cooperative and competitive interactions in a soccer match”. In: *Frontiers in Psychology* 8.AUG, pp. 1–12. DOI: 10.3389/fpsyg.2017.01379.

Rein, R. et al. (2016). “Evaluation of changes in space control due to passing behavior in elite soccer using Voronoi-cells”. In: *Proceedings of the 10th international symposium on computer science in sports (ISCSS) (pp. 179-183). Springer, Cham.*

Rein, Robert and Daniel Memmert (2016). "Big data and tactical analysis in elite soccer: future challenges and opportunities for sports science". In: *SpringerPlus* 5.1. DOI: 10.1186/s40064-016-3108-2.

Rein, Robert, Dominik Raabe, and Daniel Memmert (Oct. 2017a). ""Which pass is better?" Novel approaches to assess passing effectiveness in elite soccer". In: *Human Movement Science* 55, pp. 172–181. DOI: 10.1016/j.humov.2017.07.010.

— (2017b). ""Which pass is better?" Novel approaches to assess passing effectiveness in elite soccer". In: *Human Movement Science* 55.December 2016, pp. 172–181. DOI: 10.1016/j.humov.2017.07.010.

Reuter, Hauke and Broder Breckling (1994). "Selforganization of fish schools: an object-oriented model". In: *Ecological Modelling* 75-76.C, pp. 147–159. DOI: 10.1016/0304-3800(94)90014-0.

Reynolds, Craig W. (1987). "Flocks, herds, and schools: A distributed behavioral model". In: *Proceedings of the 14th Annual Conference on Computer Graphics and Interactive Techniques, SIGGRAPH 1987* 21.4, pp. 25–34. DOI: 10.1145/37401.37406.

Ribeiro, João, Keith Davids, et al. (Oct. 2019). "Exploiting Bi-Directional Self-Organizing Tendencies in Team Sports: The Role of the Game Model and Tactical Principles of Play". In: *Frontiers in Psychology* 10. DOI: 10.3389/fpsyg.2019.02213.

Ribeiro, João, Rui Lopes, et al. (2020). "A multilevel hypernetworks approach to capture meso-level synchronisation processes in football". In: *Journal of Sports Sciences* 38.5, pp. 494–502. DOI: 10.1080/02640414.2019.1707399.

Ric, Angel et al. (Oct. 2016). "Soft-assembled multilevel dynamics of tactical behaviors in soccer". In: *Frontiers in Psychology* 7.OCT. DOI: 10.3389/fpsyg.2016.01513.

Riley, Michael et al. (2011). "Interpersonal synergies". In: *Frontiers in Psychology* 2.MAR. DOI: 10.3389/fpsyg.2011.00038.

Robertson, R. (1995). "Glocalization: Time-space and homogeneity-heterogeneity". In: *Global modernities* 2.1, pp. 25–44.

Russell, Mark et al. (2016). "Changes in acceleration and deceleration capacity throughout professional soccer match-play". In: *Journal of Strength and Conditioning Research* 30.10, pp. 2839–2844. DOI: 10.1519/JSC.0000000000000805.

Sands, William A. et al. (Apr. 2017). *Modern techniques and technologies applied to training and performance monitoring*. DOI: 10.1123/ijspp.2016-0405.

Santana, Juliana (2011). "Representação da área de responsabilidade de jogadores de futebol através do Diagrama de Voronoi". PhD thesis. Universidade Estadual de Campinas.

Sarmento, Hugo et al. (2014). "Match analysis in football: a systematic review". In: *Journal of Sports Sciences* 32.20, pp. 1831–1843. DOI: 10.1080/02640414.2014.898852.

Schöllhorn, W. (2003). "Coordination dynamics and its consequences on sports". In: *International Journal of Computer Science in Sport* 2.2, pp. 40–46.

Shang, Yilun and Roland Bouffanais (2014). "Consensus reaching in swarms ruled by a hybrid metric-topological distance". In: *European Physical Journal B* 87.12, pp. 1–8. DOI: 10.1140/epjb/e2014-50094-4. arXiv: 1409.7491.

Silva, Pedro (2014). “Shaping Tactical Behaviours in Football: An Ecological Dynamics Approach”. PhD thesis. Universidade do Porto, p. 214.

Silva, Pedro et al. (2013). “Shared knowledge or shared affordances? insights from an ecological dynamics approach to team coordination in sports”. In: *Sports Medicine* 43.9, pp. 765–772. DOI: 10.1007/s40279-013-0070-9.

Simhon, Saul and Gregory Dudek (1998). “Global topological map formed by local metric maps”. In: *IEEE International Conference on Intelligent Robots and Systems* 3, pp. 1708–1714. DOI: 10.1109/iros.1998.724844.

Soldera, J. et al. (2015). “High Level Event Detection based on Spatial Occupancy and Interpersonal Relationships”. In: *Journal of Communication and Information Systems* 30.1, pp. 60–70. DOI: 10.14209/jcis.2015.8.

Spencer, Bart, Matthew Hawkey, and Sam Robertson (2019). “Using contextual player movement and spatial control to analyse player passing trends in football”. In: *Barça sports analytics summit*, pp. 1–12.

Steels, L. and R. Brooks (2018). *The artificial life route to artificial intelligence: Building embodied, situated agents*. Routledge.

Stergiopoulos, Yiannis and Anthony Tzes (2011). “Coverage – oriented Coordination of Mobile Heterogeneous Networks”. In: *19th Mediterranean Conference on Control & Automation (MED)*. IEEE, pp. 175–180.

Strauss, Markus J. et al. (Mar. 2017). “Suicides on the Austrian railway network: Hotspot analysis and effect of proximity to psychiatric institutions”. In: *Royal Society Open Science* 4.3. DOI: 10.1098/rsos.160711.

Sussman, Daniel M and Matthias Merkel (2018). “No unjamming transition in a Voronoi model of biological tissue”. In: *Soft Matter , Royal Society of chemistry*.

Szeto, K. (2007). “Topology for dominance for network of multi-agent system”. In: *AIP Conference Proceedings* 913, pp. 96–101. DOI: 10.1063/1.2746731.

Taki, Tsuyoshi and Jun ichi Hasegawa (2000). “Visualization of dominant region in team games and its application to teamwork analysis”. In: *Proceedings of Computer Graphics International Conference, CGI*, pp. 227–235. DOI: 10.1109/cgi.2000.852338.

Taki, Tsuyoshi and Jun-ichi Hasegawa (2000). “Quantitative measurement of teamwork in ball games using dominant region”. In: *ISPRS J Photogramm* XXXIII.1992, pp. 125–131.

Tomatis, Nicola, Illah Nourbakhsh, and Roland Siegwart (2003). “Hybrid simultaneous localization and map building: A natural integration of topological and metric”. In: *Robotics and Autonomous Systems* 44.1, pp. 3–14. DOI: 10.1016/S0921-8890(03)00006-X.

Travassos, Bruno and Duarte Araújo (2010). “Percepção de Affordances para o Passe em Desportos Colectivos”. In: *Actas do VII Simpósio Nacional de Investigação em Psicologia*, pp. 1916–1924.

Travassos, Bruno, Ricardo Duarte, et al. (2012). “Practice task design in team sports: Representativeness enhanced by increasing opportunities for action”. In: *Journal of Sports Sciences* 30.13, pp. 1447–1454. DOI: 10.1080/02640414.2012.712716.

Ueda, Fumiya, Honda Masaaki, and Horino Hiroyuki (2014). “The Causal Relationship between Dominant Region and Offense- Defense Performance - Focusing on the Time of Ball Acquisition”. In: *Football Science* 11, pp. 1–17.

Van Zwynsvoorde, D., T. Simeon, and R. Alami (2000). “Incremental topological modeling using local Voronoï-like graphs”. In: *IEEE International Conference on Intelligent Robots and Systems* 2, pp. 897–902. DOI: 10.1109/iros.2000.893133.

Vicsek, T. (2008). “Universal patterns of collective motion from minimal models of flocking”. In: *Proceedings - 2nd IEEE International Conference on Self-Adaptive and Self-Organizing Systems, SASO 2008*, pp. 3–11. DOI: 10.1109/SASO.2008.23.

Vicsek, Tams et al. (1995). “Novel type of phase transition in a system of self-driven particles”. In: *Physical Review Letters* 75.6, pp. 1226–1229. DOI: 10.1103/PhysRevLett.75.1226. arXiv: 0611743 [cond-mat].

Williams, A., K. Davids, and J. Williams (1999). *Visual perception and action in sport*. Taylor & Francis.

Withagen, Rob et al. (2012). “Affordances can invite behavior: Reconsidering the relationship between affordances and agency”. In: *New Ideas in Psychology* 30.2, pp. 250–258. DOI: 10.1016/j.newideapsych.2011.12.003.

# Empirical studies

## Chapter 4

# Team's territorial dominance in high-performance football: ball possession should not be mistaken with attacking

Caldeira, N., Lopes, R.J., Fernandes, D. & Araújo, D. (Under submission: Journal of Sports Sciences)

## Abstract

Teams' search for territorial dominance is critical to invasion games. However, its process and measurement are not clear as well as its impact on goal scoring. Arguing that territorial dominance is an expression of teams' attacking intentionality this study addresses how territorial dominance, measured by both Convex Hull - usually used as a proxy to territorial dominance - and Voronoi diagram areas, can be associated to the emergence of scoring opportunities. By comparing two measures of territorial dominance, teams' Convex Hull and Sum of Voronoi Areas (SVA), Cohen's-*d* effect size values showed that SVA is an adequate metric to assess the teams' space control during effective possession episodes (PE), and it is more precise than Convex Hull. Importantly, SVA can be used to assess teams' effectiveness, not only at the end of the PE, but also during the out of possession phase, as the territorial dominance can start before the regain of the ball's control. Overall, the study supports the ecological dynamics view that possession and attack (as out of possession and defence) are not overlapped concepts, implying the need to be addressed individually to fully understand teams' territorial dominance in tactical and strategic terms.



## Keywords

Goal-scoring opportunities; Team performance; Team synergies; Voronoi diagrams; Convex hull

## 4.1 Introduction

In high-performance football, winning is the immediate goal that guides teams, players and coaches when playing a match. Football matches can be codified as a zero-sum game (Hirotsu et al., 2009), as the gain in probability of one team winning is equal to the loss in probability of the other team winning. Football is also an invasion game (Kirk and MacPhail, 2002), as the two teams compete in the same physical space. This feature implies the competition for territorial dominance as a key aspect for winning the match. This idea is aligned with that from Thorpe and colleagues who defined matches as “a struggle for territorial dominance within a set of rules […] decided by a system of scoring which symbolises the extent of victory” (Thorpe, Bunker, and Almond, 1986, p73). In this context, the current paper aims to clarify how goal scoring opportunities are associated with ball possession and territorial dominance, measured as it is discussed next.

### 4.1.1 The concept of *territorial dominance*

Being an invasion game, football association is a dynamic social system where “agents interact continuously to contest ball possession and seek territorial advantage” (Correia et al., 2011, p662). The football match as well as other team sports such as Rugby, Basketball or Handball show “common tactical features of invading territory” to reach a “goal or similar target for scoring” (Kirk and MacPhail, 2002, p179). Before the kick-off, it is clear that each team is placed in its own half pitch as their territory. However, as the match evolves it is no longer so clear who dominates which territory. Nonetheless, the only way to score is by invading the opponent’s defensive territory to approach their goal, highlighting the need to scientifically understand territorial dominance.

It is useful to consider the definition adopted by the dictionary of the American Psychological Association (American Psychological Association, 2015) of territorial dominance: a) “in animal behaviour, the ability of resident animals to protect a defined space (their territory)”; and b) “the tendency of people to dominate interpersonal interactions to a greater extent when in their own homes or offices”. In nature, several works (Moreau et al., 2011; Takeuchi, 2011) have shown that the ability to protect a physical space as its territory, is dependent on different animal organismic constraints, like the size, weight, or other body dimensions and morphology.

In football, these ideas are reflected in the tendency for teams to obtain better results when playing in their stadium, the home-advantage effect (Carmichael and Thomas, 2005). Likewise, it is clear the importance of seeking to gain individual duels to ensure control of a territory over the opponent (Carling, Dupont, and Le Gall, 2011), or to collectively obtain numerical superiority in a certain area of the pitch (Vilar et al., 2013; Goes et al., 2020). In the match dynamics it is clear that territorial dominance can only be achieved, individual or collectively, if it is possible to reach a given space before the opponents. This tendency is echoed in sport sciences’ literature using variables such as space control (Rein, 2016), occupied space (Rico-González et al., 2020) or sphere of influence (Taki and Hasegawa, 2000) as proxies for *territorial dominance*.

### 4.1.2 Territorial dominance, ball possession and attacking effectiveness

The classical view of tactical methods in team sports (Teodorescu, 1984) and football (J. F. Gréhaigne, Bouthier, and David, 1997) considers that the struggle for territorial dominance is overcome by team's ball possession status. Considering the spatial-temporal aspects of territorial dominance, the team that has the ball must attack the opponent's territory in order to reach their goal. Concomitantly, the opposite must be done by the team that does not have possession of the ball which must defend its territory and goal. Therefore, the notions of attacking and defending tend to be linked to the circumstance of a team having or not (respectively) the possession of the ball.

However, as highlighted by Araujo and colleagues (2016), when we consider high-level matches, this distinction between attacking and defending, depending on ball possession status, is an oversimplification. Notably, there are periods where the team "in possession" is not attacking the opponent's territory, simply maintaining the ball to defend a lead. Similarly, there are moments where a team is "out of possession" but shows intentional attacking movements. This is evident when a team invades the opponent's territory to pressure the ball carrier (Gesbert and Durny, 2017), and/or the spaces of their teammates (Andrienko et al., 2017), to recover the ball as close as possible to the opponent's goal and score (C. Hughes, 1990). Supported by teams' high-pressure tactics (Low, Rein, et al., 2021), situations where a team recovers the ball near the opponent's goal can explain why some of the most effective ball possession episodes (PE) are very brief match sub-phases (M. Hughes and Lovell, 2019). Therefore, despite its importance (Lago-Peñas and Dellal, 2010), ball possession *per se* cannot consistently be tied to team success (Collet, 2013).

From an attacking perspective, ball possession effectiveness seems to be more decisive than the duration of each ball possession episode or the match overall possession percentage (González-Rodenas et al., 2020; M. Hughes and Franks, 2005). This effectiveness in a low-score game like football cannot be measured only by the number of goals (Sarmento et al., 2014). Instead, it should be inferred via events that are linked with the creation of goal scoring opportunities such as shots, crosses or pass-assistances (Mitrotasios, Gonzalez-rodenas, and Armatas, 2019; González-Rodenas et al., 2020; Ueda, Masaaki, and Hiroyuki, 2014). Consequently, if a team's territorial dominance is an expression of its attacking intention, it will be possible to identify a link between territorial dominance and the effectiveness of ball possession episodes (PE).

In summary, to understand the emergence of goal scoring opportunities during a football match, we argue that territorial dominance is an expression of a more pronounced team attacking intention. This includes the moments when the team is not with the ball (out of possession phase). In this sense, the status of ball possession may not be time coincident with teams' global attacking intention, and their inherent quest for territorial dominance.

### 4.1.3 The assessment of the territorial dominance in football

An important feature of all zero-sum invasion games is the interactions between cooperating and competing players, to achieve the competitive performance aims of each team (Araújo and Davids, 2016). Due to the relevance of these interactions, behaviour of sport teams can be addressed by the concept of synergies and their properties (Araújo and Davids, 2016). Research into synergies in sport is supported by the idea that the behaviour of a team (originally a high-dimensional system) can be summarised by a few low-dimensional variables or even a single collective variable. This property of dimensional compression (Araujo et al., 2017) is evident when a unique collective variable captures (compresses) all the independent degrees of freedom (dimensions) of the elements of a team (i.e., players behaviours). For example, the team's centroid can express in a single variable players' forward-backward (or side-to-side) collective movement displacements (Araújo and Davids, 2016; Frencken and Lemmink, 2008). Although it reflects teams' global to-and-fro in the pitch, teams' centroids hardly clarify the possible territorial dominance of one team over the other. A possibility to assess the *rapport of forces* (J. Gréhaigne, Godbout, and Zera, 2011) between the two competing teams is through the numerical (in)balance that exists in a certain pitch area. To calculate such an area researchers computed either from the division of the entire pitch in a certain number of fixed regions (Filipe Manuel Clemente et al., 2015) or the effective playing space (J. F. Gréhaigne, Bouthier, and David, 1997) in a set of dynamic zones (Vilar et al., 2013).

Nevertheless, even in a dynamic approach, this kind of variables only capture the number of elements in each area of the pitch, falling short in understanding teams' behaviour. In alternative, two types of metrics are widely used to assess the space occupied by a team (Rico-González et al., 2020):

a) Metrics that capture team's expansion or contraction in the pitch that, jointly with the teams' centroids, express territorial dominance. Examples are the stretch index (Bourbousson, Sève, and McGarry, 2010) and the Frobenius norm (Moura et al., 2012); and

b) Metrics that measure team's absolute dispersion, which calculate the space occupied by the entire team or a group of players. This can be computed by the product of teams' width and length (Folgado et al., 2012), or by the polygon limited by its Convex Hull (CH). CH is also known as the surface area of the team (Ramos et al., 2020), and related to the concept of effective play-space (J. F. Gréhaigne, Bouthier, and David, 1997) or density of the team (Timmerman and Farrow, 2017). Research shows that teams' CH is highly variable, with important differences between the moments when a team is with or without the ball (Bartlett et al., 2012; Moura et al., 2012).

About a), a general pattern of expansion-contraction according to the in possession and out of possession ball status was initially identified as being the most common (Filipe M. Clemente, Couceiro, and Martins, 2012; Moura et al., 2012). However, the idea that the "defending" team contracted while the "attacking" team expanded was not supported by Bartlett and colleagues (2012) who found that an expansion-contraction pattern was only evident in 28% of the attacks.

For b), Frencken and Lemmink (2008), using small-sided games, concluded that the synchronisation between the CH of both teams' did not show a clear anti-phase relation. Albeit this criticism, team's CH can be useful when properly contextualised to the match dynamics sub-phases, as showed by Moura and colleagues as they concluded that "in defending circumstances, the teams presented a greater area and spread when they suffered shots on goal than when the teams performed tackles" (Moura et al., 2012, p85). Therefore, CH seems to have the capacity to express, to some degree, teams' expansion-contraction patterns, even if it remains unclear the extent of their territorial dominance and how this is associated to the emergence of scoring situations and goal opportunities. For this reason, this paper aims to operationally clarify the relevance of CH as a proxy of teams' territorial dominance and how it is related to the effectiveness of the attacking processes.

In addition, in the present paper, the same approach is taken for Voronoi diagrams (VD), tessellations that define the area that is closer to a given point than to any other point, in a given space (Kim, 2004). In football context, VD are based on players' positional data on the entire pitch where they act (Taki and Hasegawa, 2000; Ueda, Masaaki, and Hiroyuki, 2014) and are used as a measure of players' and teams' areas of influence (Rico-González et al., 2020). Despite its limitations due to the unrealistic assumption that "all players are equally fast, start from a static position, and can infinitely accelerate" (Rein, Raabe, and Memmert, 2017, p179), VD seem to be useful to assess how players of both teams "divide" the space among them. In practical terms, even in a match context that has a chaotic background (Mateus, 2005), it remains plausible the basic idea of using the Euclidean distance to construct VD cells of individual player's (Rein, Raabe, and Memmert, 2017). In fact, if the VD computation is based, not only in the positions of players from a single team (Santana, 2011) but, in all players of both teams (Fonseca et al., 2012) they will capture the globality of spatial interactions in a given instant on the football pitch. In the context of team sports, Voronoi diagrams (VD) have been used to evaluate individual and team territorial dominance (Fonseca et al., 2012; A. Lopes et al., 2013; António Lopes et al., 2015; Perl and Memmert, 2016), notably "the proportion of space owned by a team" (Spencer, Hawkey, and Robertson, 2019, p1777). With this in mind, the information present in a VD, can be summarised in a collective variable that dimensionally compresses global teams' behaviour: the Sum of the Voronoi Areas (SVA) of each team.

In this paper we posit that, operationally, teams' SVA and Convex Hull (CH), are indicators of teams' territorial dominance. It is also proposed that these variables can distinguish between effective and not effective possession episodes, being able to capture the conceptual link between teams' territorial dominance and the attacking intention that underlies the emergence of goal scoring opportunities.

## 4.2 Materials and Methods

### 4.2.1 Data sources

This study was supported by the positional data of 20 matches from the French main football league (2019-2020 season). Data was obtained and processed by the company STATS©, through their systems of semi-automatic tracking, as validated by Di Salvo and colleagues (Di Salvo et al., 2006). The match's raw data, i.e., the longitudinal and lateral coordinates of all the 22 players and ball position, were sampled at 10Hz. In addition to positional data, match events (representing players' contacts with the ball) and possession episodes (PE) information (time initial and final instants), where also provided by STATS©. According to STATS© definitions manual, a PE "is maintained even if the opposition disrupts play with one single event (i.e., at least two consecutive events are necessary to form a possession)" (STATS, 2019).

### 4.2.2 Data processing

Data was filtered so that only open plays are considered, i.e., set plays and time gaps without play were discarded. For the 20 matches a total of $K = 4198$ ball possession episodes (PE) were considered. Each open play possession episode (PE), $k = 1, \ldots, K$, was classified by identifying:

- the team in ball possession, $T_I$, and the team out of possession, $T_O$;
- its effectiveness, $Eff(k)$, as "Effective Possession" $(Eff(k) = Ep)$ or "Not effective Possession" $(Eff(k) = Np)$ A possession episode is classified as "Effective Possession" $(Ep)$ if it contains at least one of the following events: `Goal`, `Shot On Target`, `Shot Not On Target`, `Cross`, `Cross assistance` or `Pass assistance`, as defined by (STATS, 2019), Yoshimura (2003) and Ueda and colleagues (2014). From the 4198 ball possession episodes, 841 were classified as effective possessions $(Ep)$ and the remaining 3357 as not effective possessions $(Np)$.
- its initial, $t_{i,k}$, and final instants, $t_{f,k}$; corresponding respectively to ball recovery and the frame immediately before a finishing event or ball loss by the team in possession. For each frame, $t$, of open play possession episodes, are obtained (see Figure 4.1):

  a. the area, $CH_{T_i}(t)$, of the convex hull (CH) of each team, $T_i$, computed as the smallest polygon containing all outfield players (not considering, therefore, the goalkeepers), as described by Moura and colleagues (2012).

  b. the area, $VA_j(t)$, of the Voronoi cell of each player, $j$, computed using the procedures described by Kim (2004). For each team, $T_i$, the Sum of the Voronoi Areas, $SVA_{T_i}(t)$, is computed as proposed by Fonseca and colleagues (2012) as the sum of the individual areas of their respective players, $SVA_{T_i}(t) = \sum_{j \in T_i} VA_j(t)$.

     ($j \in T_i$ is read as: player $j$ is part of team $T_i$.)

  c. the relationship between the areas of both teams, as the ratio $(I/O)$ computed by dividing the areas of the team in possession, $T_I$, by areas of the team out of possession, $T_O$. This ratio is given respectively, for the $CH$ and $SVA$ variables by: $CH_{I/O}(t) = \frac{CH_{T_I}(t)}{CH_{T_O}(t)}$ and $SVA_{I/O}(t) = \frac{SVA_{T_I}(t)}{SVA_{T_O}(t)}$.

     Given that the Voronoi cells cover the pitch completely, the following relation holds for the $SVA$

variable:

$$SVA_{T_I}(t) = FieldArea - SVA_{T_O}(t) \tag{4.1}$$

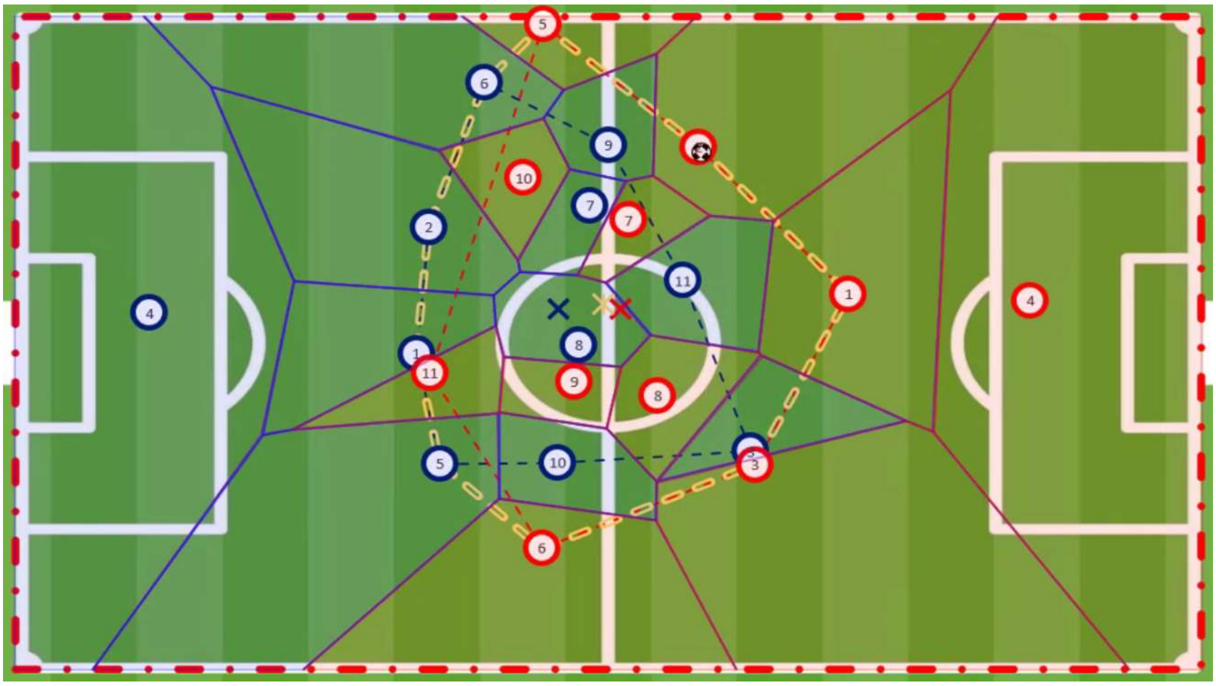


**Figure 4.1:** One time frame Voronoi diagram and convex hulls.
*Voronoi diagram players' cells (red and blue polygons); match and teams' centroid (yellow, blue and red crosses); convex hull for the match (dashed yellow polygon), in possession team (dashed red polygon) and out of possession team (dashed blue polygon).*

The previous metrics are structured into ball possession episodes (PE) time-series, as exemplified in Figure 4.2. This figure shows the time-series values for the Sum of Voronoi Areas ($SVA$) and Convex Hull ($CH$) of both teams, during a ball possession episode (since the recovery until the loss of the ball by a team). As highlighted in Figure 4.2, values are taken at the first and last frame of each PE and its mean value computed.

### 4.2.3 Statistical analysis methods

The statistical analysis was performed to investigate the frequency distributions of different data series, using violin plots, and check if differences between pairs of these data series had statistical significance, assessing their effect size. For the latter, $t$-test and Cohen-$d$ measures were computed. Although there is no prior indication of the normality of the data series, $t$-tests were used due to the data series size (see Cessie and colleagues (2020). An independent $t$-test was used in all considered pairs, with the exception of the "in possession"/"out of possession" study in Section 4.3.1. All tests are two-sided with null hypothesis of similar means and the alternative hypothesis being adopted if $p < .05$.

The practical relevance (Aarts, Van Den Akker, and Winkens, 2014) of the differences was determined through the computation of their effect size (Cohen's-$d$), with 95% confidence intervals. Effect sizes magnitudes were classified according to Cohen (1988) and Sawilowsky's (2009) rules of thumb: $d < .2$

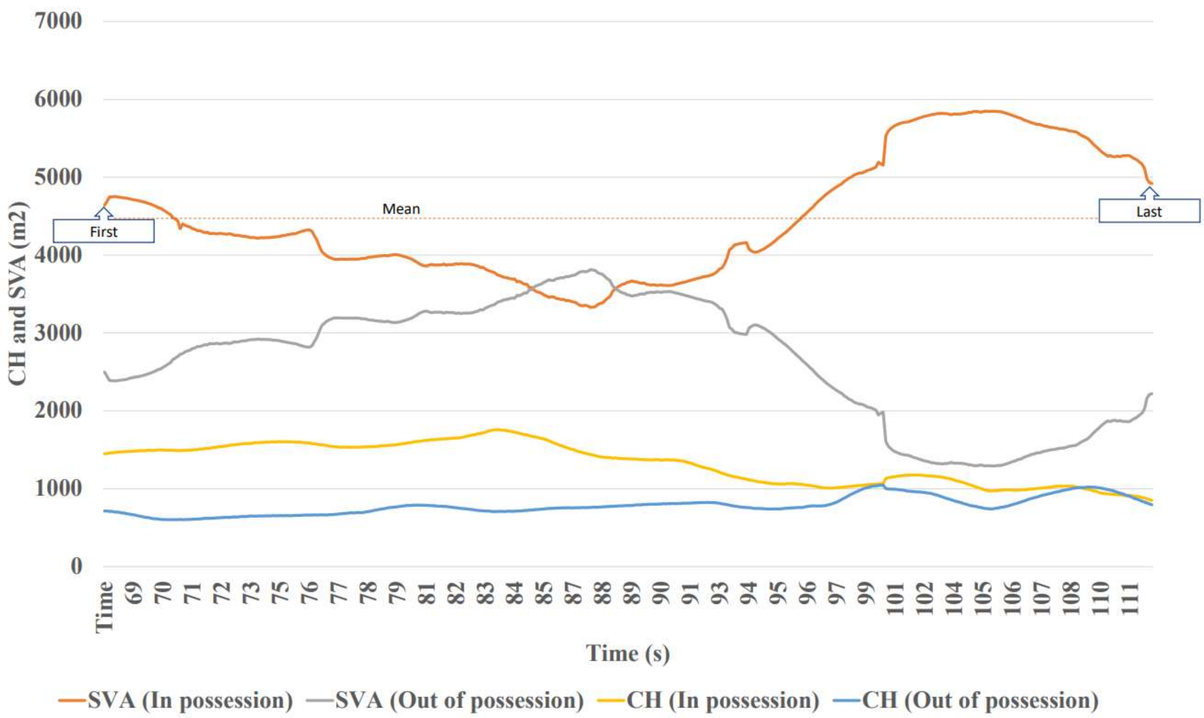



**Figure 4.2:** $SVA$ and $CH$ time-series during a PE, for the teams *in possession* and *out of possession*

(very small); $d < .5$ (small); $d < .8$ (medium); $d < 1.2$ (large); $d < 2.0$ (very large) and $d >= 2.0$ (huge). Identically procedure was taken to compare the time-series regularity. For this purpose, the approximate entropy ($ApEn$), as described by Pincus (1991), was computed for each possession episode time-series with a minimum of 50 data points (corresponding to 2666 $Np$ and 707 $Ep$ episodes). $ApEn$ was calculated for:

a) $SVA$ and $CH$ absolute values for teams in possession and dispossession and for their "$I/O\ ratio$"; and

b) the "rate of change" ($RoC$) of these variables computed as the relative variation between one frame and the next, for example, the RoC for the SVA I/O ratio is given by: $SVA_{I/O(roc)}(t) = \frac{SVA_{I/O}(t+1)}{SVA_{I/O}(t)} - 1$.

## 4.3 Results

The results on the distributions, differences and dynamics of $SVA$ and $CH$ metrics are organised as follows: a) SVA and CH metrics are analysed according to teams' ball possession status (Sections 4.3.1 and 4.3.2); and b) Comparison of the effectiveness of ball possession episodes through the comparison of $SVA$ and $CH$ metrics and respective time-series approximate entropy ($ApEn$) (Section 4.3.2). The numerical values for all the results presented are provided as Supplementary Material.

### 4.3.1 CH and SVA differences according to teams' ball possession status

The results of comparing the $CH$ and $SVA$ areas, according to ball possession status (in possession vs out of possession) are presented in the violin plots of Figure 4.3.

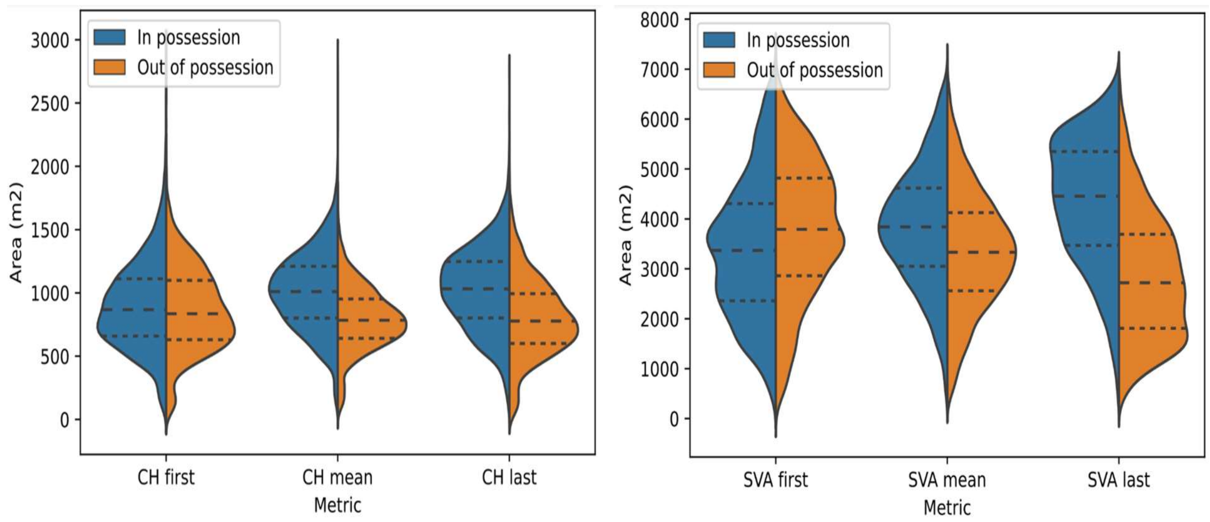



**Figure 4.3:** Violin plots of CH and SVA areas according to ball possession status

As shown in Figure 4.3, the status of ball possession (in possession vs out of possession) clearly influences teams' territorial dominance. Higher values in possession team values were statistically significant ($p < .05$), whether the territorial dominance was quantified through teams' Convex Hull area ($CH$) or by their Sum of the Voronoi Areas ($SVA$), except for their first instant. However, the respective Cohen's-$d$ effect size showed distinct magnitudes of these differences (Figure 4.4)

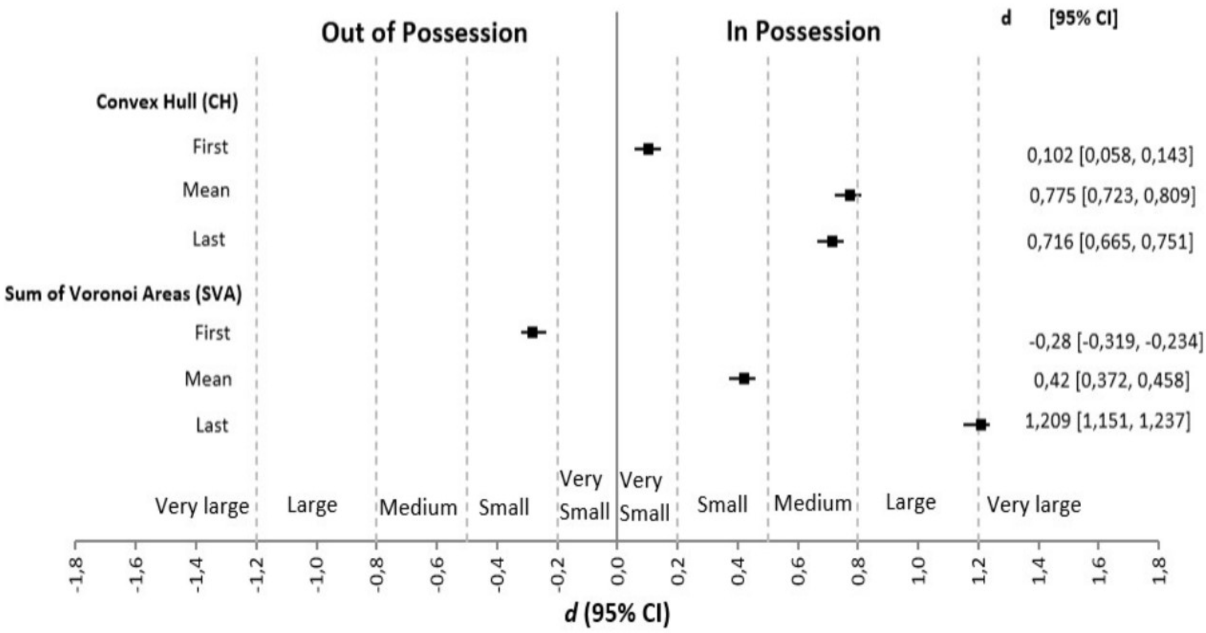



**Figure 4.4:** Forest plot of the effect size of the differences of $CH$ and $SVA$ areas, according to ball possession status

### 4.3.2 CH and SVA differences according to ball possession episode effectiveness

Classifying the time-series possession episodes by their effectiveness, effective ($Ep$) and not effective ($Np$), important differences between the two variables ($CH$ and $SVA$) arise. We address these differences from two perspectives:

a) comparing team's absolute values and $I/O\ ratio$ using the first, last instants and the mean value of the possession episodes time-series; and

b) comparing the possession episodes time-series approximate entropy ($ApEn$).

#### Comparison of absolute values and I/O ratio

The differences between $Np$ and $Ep$, in each variable can be observed in the violin plots of Figures 4.5(a) in possession team, 4.5(b) out of possession team and 4.5(c) $I/O\ ratio$.

All differences were statistical significant ($p < .05$), except the first instant of the $CH$ time-series for the possession team (marked with * in Figure 4.6 ). In addition, Figure 4.6 illustrates the forest plot of the respective effect size (Cohen's-$d$).

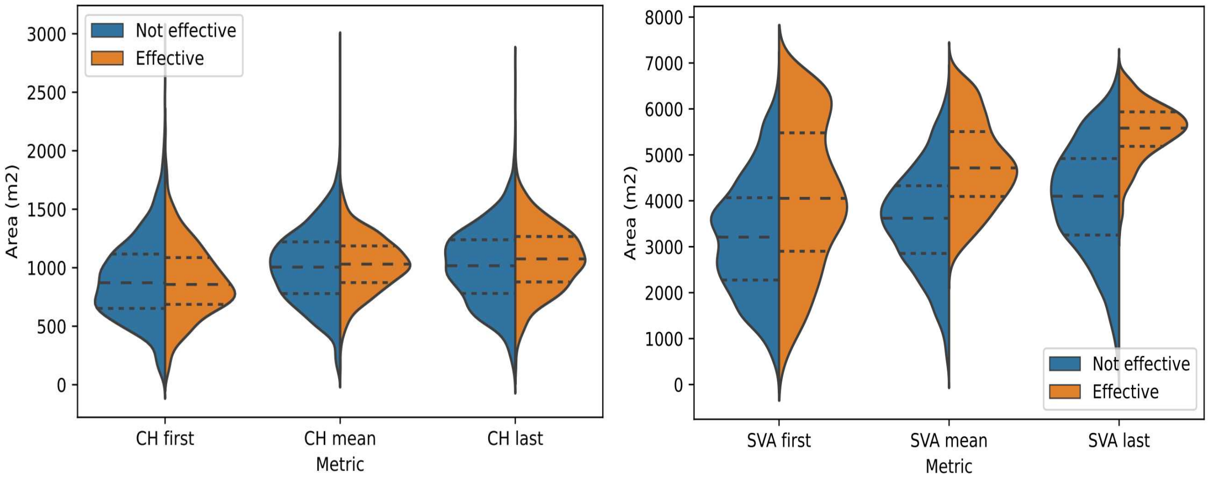
Small or very small effect sizes were observed for the CH values of both teams and for the CH I/O ratio observed at possession episode last frame. Medium effect sizes were observed for the $CH\ I/O\ ratio$ mean and first frame of the possession episode. The negative effect sizes values indicate that out of possession teams' contract more in effective PE than in not effective PE.

Medium effect sizes were also observed for the SVA values of the in possession and out of possession teams in the first frame of the possession episode. Large and very large effect sizes were observed for the mean and last instant SVA values for both teams and for all $SVA\ I/O\ ratios$. The positive sign for the effect sizes for the possession team and $I/O\ ratio$ indicate that the possession team has more territorial dominance in effective PE than in not effective PE. Due to the symmetrical nature of the $SVA$ variable (see Equation 4.1), for the same cases, the effect size signal is negative for the team out of possession.

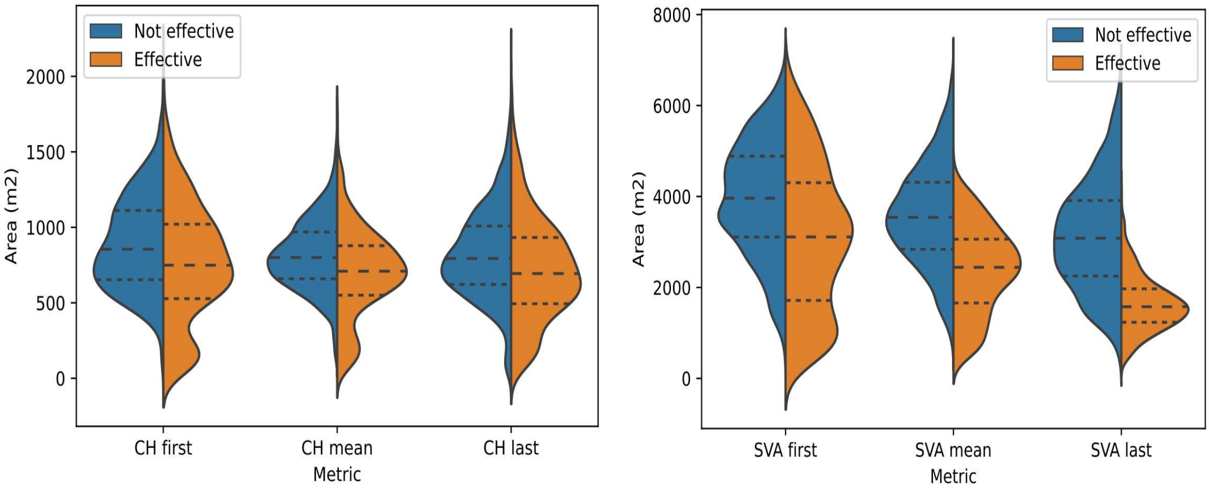
#### Comparison of time-series approximate entropy (ApEn) means

Figure 4.7 shows the distribution of the approximate entropy ($ApEn$) for the teams' $SVA$ and $CH$ absolute values and $I/O\ ratio$ (Figure 4.7(a)), and their Rate of Change (Figure 4.7(b)). Results are shown according to the effectiveness of the possession episode.

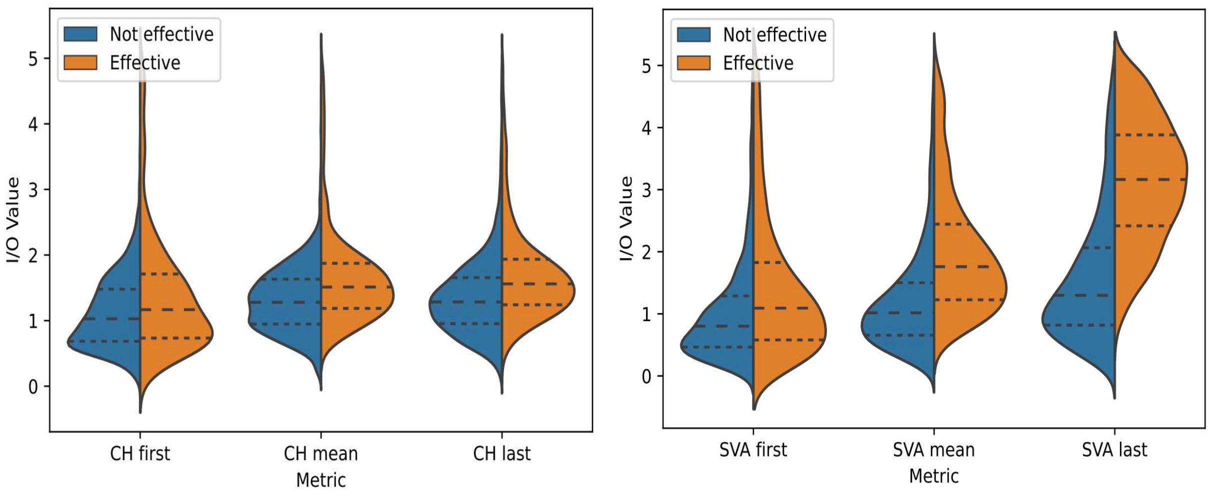
In general, the ApEn values obtained from $CH$ or $SVA$ absolute values (or $I/O\ ratio$) were very low showing a relative regularity of the respective time-series. On the other hand, much higher values were observed when the $ApEn$ was calculated in relation to the CH's and SVA's Rate of Change ($RoC$). The results from the two-sided independent $t$-test shown that the null hypothesis (similar means) could not be rejected for the $CH$ metric (in possession $p = .78$, out of possession $p = .083$, $I/O\ ratio\ p = .66$), for the remaining cases the differences were not statistically significative ($p < .05$).




**(a)** In possession.




**(b)** Out of possession.




**(c)** I/O ratio.

**Figure 4.5:** Comparison of $CH$ and $SVA$ areas according to ball possession effectiveness ($Np$ vs $Ep$).

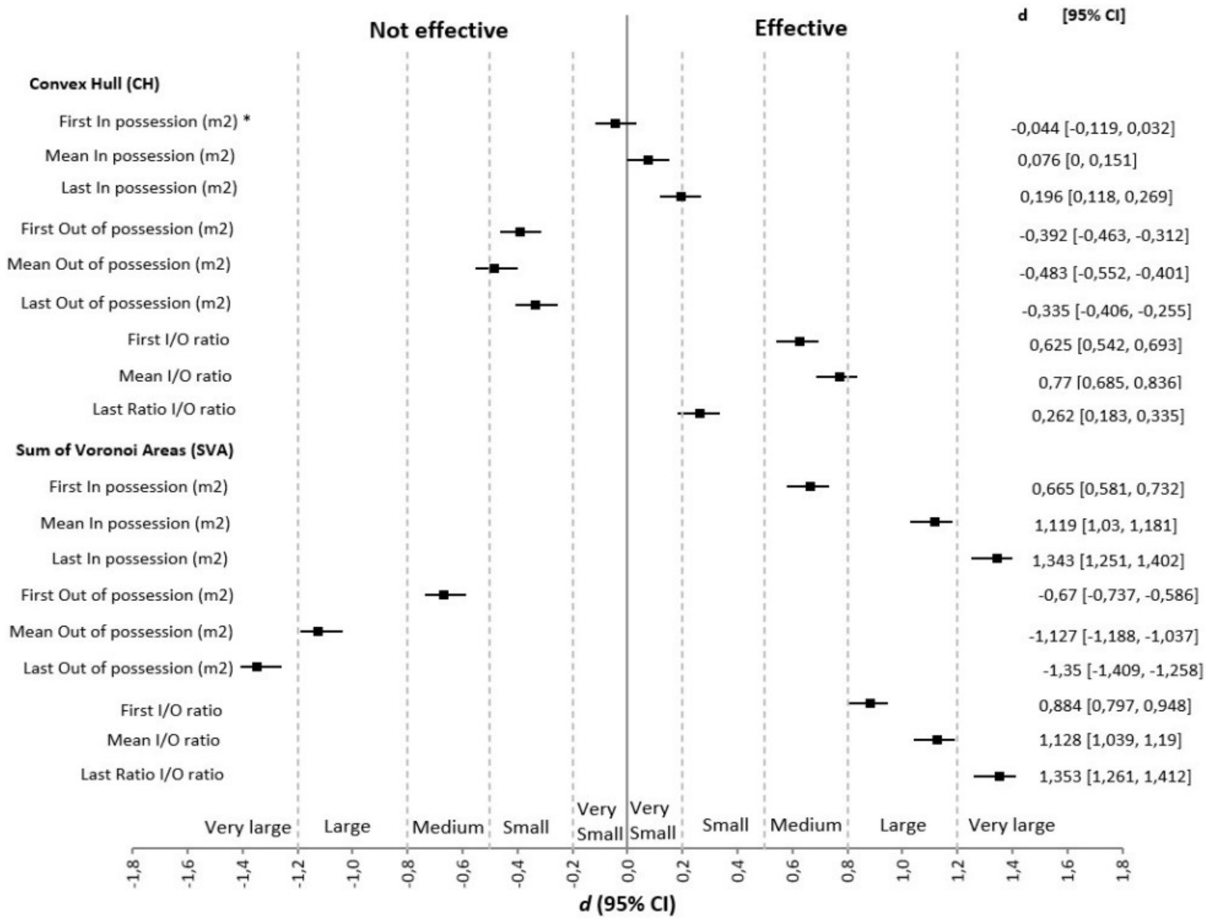



**Figure 4.6:** Forest plot of the effect size of the CH and SVA differences by possession episodes effectiveness (Np vs Ep)

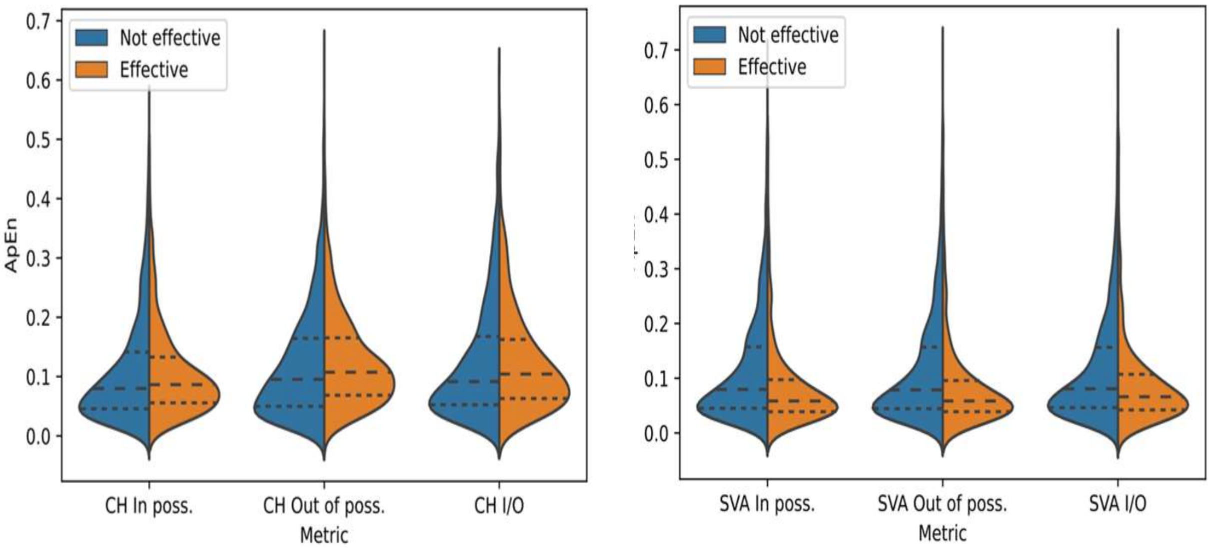
As shown in Figure 4.8, although some differences between $Ep$ and $Np$ were statistically significant (non significant marked with *), the effect sizes are small or very small for all $ApEn$ metrics considered.

## 4.4 Discussion and Conclusions

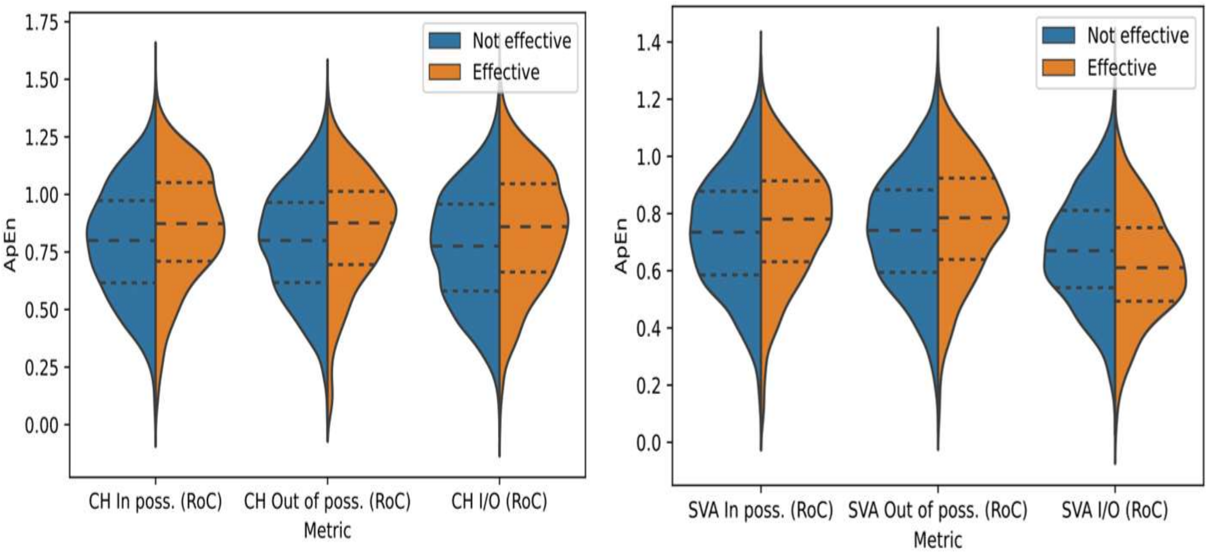
The aim of this study was to investigate, in high-performance football, how territorial dominance can be quantitatively assessed regarding its relation to ball possession and its effectiveness for goal scoring opportunities.

The results obtained (Figure 4.3) confirm mostly the well-known link between ball possession status and territorial dominance (Moura et al., 2012). This effect was present in all *Convex Hull* (CH) metrics (first and last instant and mean value) whilst for the *Sum of Voronoi Areas* (SVA) this occurs only for mean value and last instant of the time-series. In fact, in the first instant of the possession episodes (PE), the team in possession tends to have a smaller SVA than the opponent (with a negative effect size) (Figure 4.4).

It is interesting to note that the effect sizes for CH mean value are slightly bigger than for the last instant, which might be justified by the fact that the approximation to the opponents goal typically implies a smaller CH for the team in possession of the ball. On the other hand, the $SVA$ values obtained at the final instant




**(a)** CH and SVA absolute values.




**(b)** CH and SVA rate of change (RoC).

**Figure 4.7:** ApEn comparison of CH and SVA according to ball possession effectiveness (Np vs Ep).

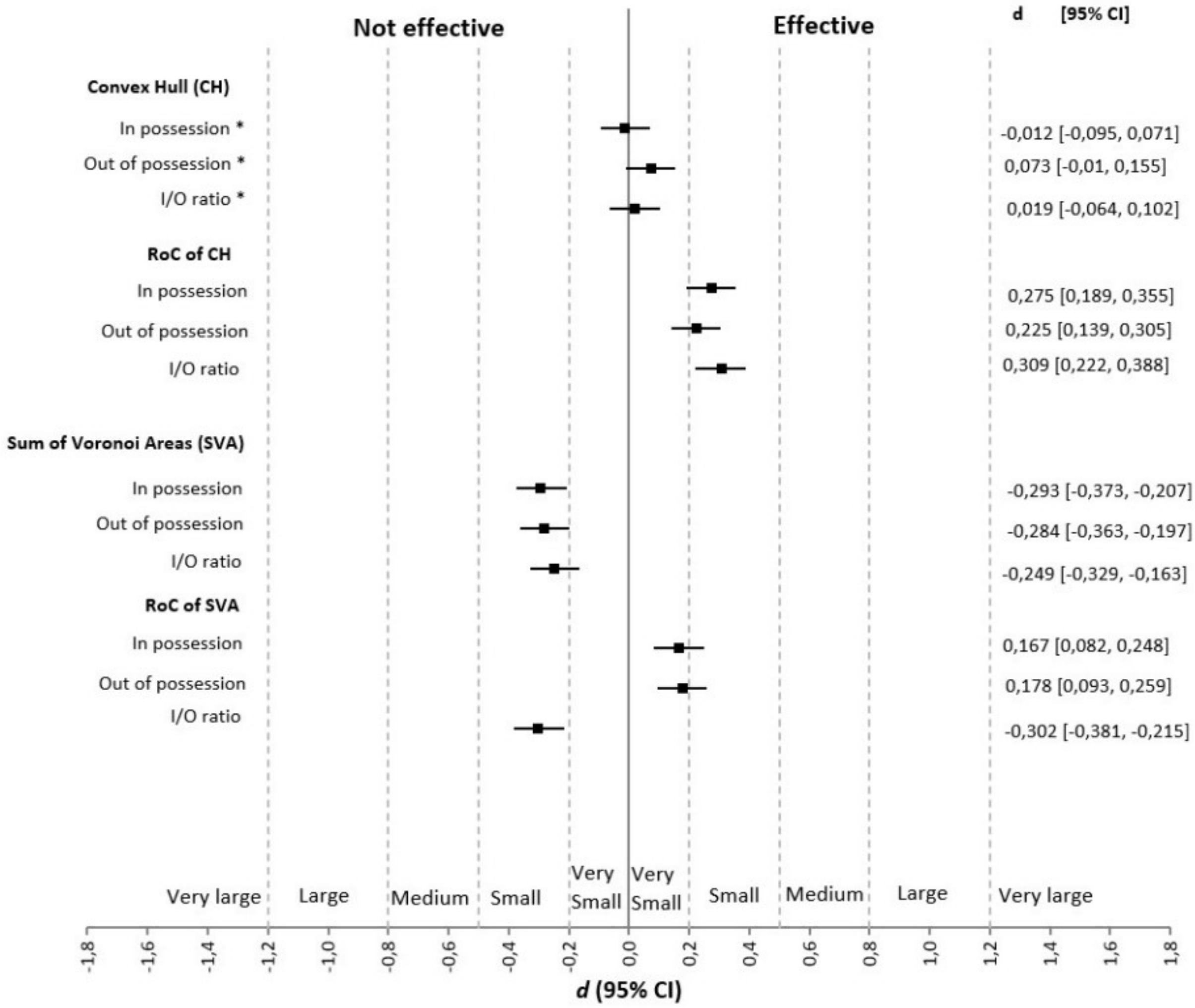



**Figure 4.8:** Forest plot of the effect size of the differences by possession episodes effectiveness (Ep vs Np), for the ApEn of teams' SVA and CH time-series

of the PE are more discriminative between the teams in and out of possession of the ball. This is likely associated to the approximation to the goal of the out of possession team and large Voronoi cell areas of the in possession team players closer to their own goal.

The other goal of the study was related to the effectiveness of the ball possession episodes (PE), notably to assess the impact of territorial dominance, quantified by CH and SVA metrics, on the success of a PE. To test this hypothesis, values for $Ep$ and $Np$ cases were compared and the overall results (Figure 4.5) indicated that for most metrics, there were statistical differences between these two types of PE (the only exception being the CH taken at the first instant of the PE).

The effect sizes of $SVA$ differences obtained at the last instant of the PE standout as very large (Figure 4.6). This was expected, as effective possession episodes of the team tend to finish closer to the out of possession team goal, corresponding to larger space control or dominance (Rein, 2016) for some of the players of the in possession team. Interestingly, the same is not found for the $CH$ metric, providing more evidence for the hypothesis about the impact of the approximation to the opponent's goal on the in possession team's $CH$.

Another important result is that the relevance of $SVA$ is beyond the last instant of the possession episodes time-series. Results demonstrated how the effective PE were marked by a greater territorial dominance in all its duration (mean of the PE), as well in its first instant. This is relevant because the first instant indicates a tendency for the effective PE to start with territorial dominance. These differences in the first instant $SVA$ values (and out of possession team $CH$ area or $CH\ I/O\ ratio$), may reflect the importance that in nowadays football is given to collective pressure (Andrienko et al., 2017). In fact, the high-pressure since the first stages of the opponent building up phase (Low, Rein, et al., 2021), seems to be crucial to teams' performance at the high-level. The same applies to team's coordination in "counterpressing", i.e., the ability to apply pressure on the opponent immediately after losing the ball, to regain the ball as fast as possible (Bauer and Anzer, 2021).

Therefore, these results showed why territorial dominance is important to team's effectiveness, regardless of the ball possession status. In fact, the main purpose of the attacking process (an initiative to score goals) is also dependent on what is accomplished during the time out of possession, leading many coaches to conclude that adopting high-pressure strategies can be beneficial (Low, Boas, et al., 2018).

Consequently, even if a greater control of the ball possession has a clear implication on team's performance (Pratas, Volossovitch, and Carita, 2018), we agree with Collet (2013, p123) when he argues that "ball hegemony was not consistently tied to success". This observation suggests the importance of coaches to practice different global strategies that promote territorial dominance with an impact on local relations that are established between the two teams. The attacking process probably begins before the recovery of the ball, i.e., during the "out of possession" phase or in the brief phase-transition moments, by reaction to the ball loss to an immediate ball recovery (for example, through the mentioned counterpressing). This implies that the concepts of attacking and ball possession, as well as those of defending and out of possession do not overlap (Mateus, 2005). For example, the team synergies linked to the collective intelligence (Duarte and Frias, 2011) required to execute a coordinated high-press (Low, Rein, et al., 2021) to close opponent spaces and recover the ball can be seen as simultaneously pursuing defensive and attacking objectives or "two sides of the same coin" (Araújo and Davids, 2016, p2).

Controlling the ball implies "Possession Episodes" and not necessarily "Attacking Episodes". However, the confusion between these concepts is pervasive in the literature. For example, Fonseca and colleagues (2012, p1656) indicated that "in comparison to what was found in the defender team, the area occupied by the attacker team is much more variable within each frame". Such variability was addressed in the present study with approximate entropy ($ApEn$), to check if there were differences between effective and not effective PE time-series regularity (Figures 4.7 and 4.8). Even with small magnitudes, we found that the absolute areas of $SVA$ showed a negative effect size with a greater $ApEn$ in the not effective time series (without finishing events), whilst for $CH$ and $SVA$'s absolute values rate of change (RoC), the effect size was positive. This means less regularity in the RoC time series in effective PE, a difference that may be associated with a greater unpredictability in the pace at which the territorial dominance by the team in possession takes place, thus underling a higher turbulence associated to possessions with an "initiative to score" (Araújo and Davids, 2016, p2).

In not effective PEs there was a greater regularity (lower $ApEn$) in the $CH$ and $SVA$ rates of change, possibly linked to a greater balance between the teams. This balance in the territorial dominance can prevent the team in possession from enhancing effectiveness in attacking. Additionally, it may also indicate that teams use ball possession to "prevent the other team from scoring" (Araújo and Davids, 2016, p2), with a more defensive intention and less sudden changes in the pace of the game and possibly obtaining territorial gains.

In conclusion, this study found a link between the territorial dominance of a team and the effectiveness of ball possession episodes, expressed in opportunities to score goals. Moreover, the territorial dominance linked to the possession effectiveness seems to be captured more accurately through the Sum of Voronoi Areas ($SVA$) than team's Convex hull ($CH$) (Moura et al., 2012).

In fact, team's attacking intention can be perceived even before it has gained the possession of the ball, using its territorial dominance over the opponent, which translates into an increase in its effectiveness in the subsequent ball possession episode.

For this reason, we advocate, at least in the context of high-performance football, that the concepts of possession and out of possession of the ball should not be overlapped with those of attack and defence, as it tends to happen in the literature. Such a confusion makes it difficult to design a better practice for the development of players and teams.

## Notation

| | |
|---|---|
| ApEn | Approximate Entropy |
| CH | Convex Hull |
| Ep | Effective Possession |
| I/O | In Possession / Out of Possession |
| Np | Non Effective Possession |
| PE | Possession Episode |
| SVA | Sum of Voronoi Areas |
| VD | Voronoi Diagram |


## Acknowledgement

All data was kindly provided by the STATS© company.


## Disclosure statement

The authors declare no conflict of interest.

## Funding

Duarte Araújo was partly funded by the Fundação para a Ciência e Tecnologia (grant number UIDB/00447/2020, awarded to CIPER-Centro Interdisciplinar para o Estudo da Performance Humana (unit 447). Rui J. Lopes was partly supported by the Fundação para a Ciência e Tecnologia, under Grant Number UIDB/50008/2020 attributed to Instituto de Telecomunicações.

## Data availability

Data was obtained from STATS© company and are available from STATS© with their permission.

## Author contributions

Conceptualisation, N.C., R.J.L. and D.A.; Data curation, N.C., R.J.L and D.F.; Formal analysis, N.C. and R.J.L.; Funding acquisition, D.A.; Investigation, N.C., R.J.L. and D.A.; Methodology, N.C., R.J.L. and D.A.; Software, D.F.; Visualisation, N.C., R.J.L. and D.F.; Supervision, R.J.L. and D.A..; Writing—original draft, N.C.; Writing—review and editing, R.J.L. and D.A. All authors have read and agreed to the published version of the manuscript.

# Supplementary Material: Additional statistical data

**Table 4.1:** Mean, first and last time-series $CH$ and $SVA$ values for the possession episodes with (In possession) or without ball (Out of possession)

| | | In Possession ($m^2$) | | Out of Possession ($m^2$) |
|---|---|---|---|---|
| **Convex Hull ($CH$)** | | | | |
| $First$ | Mean | 910.9 | | 888.1 |
| | SD | 346.5 | | 318.6 |
| | $t$-test ($p$) | | $< .001$ | |
| $Mean$ | Mean | 1049.6 | | 806.6 |
| | SD | 287.1 | | 228.1 |
| | $t$-test ($p$) | | $< .001$ | |
| $Last$ | Mean | 1068.8 | | 818.8 |
| | SD | 305.8 | | 308.0 |
| | $t$-test ($p$) | | $< .001$ | |
| **Sum of Voronoi Areas ($SVA$)** | | | | |
| $First$ | Mean | 3298.0 | | 3868.3 |
| | SD | 1282.9 | | 1282.3 |
| | $t$-test ($p$) | | $< .001$ | |
| $Mean$ | Mean | 3834.2 | | 3333.2 |
| | SD | 1038.3 | | 1037.3 |
| | $t$-test ($p$) | | $< .001$ | |
| $Last$ | Mean | 4446.0 | | 2720.3 |
| | SD | 1131.2 | | 1130.8 |
| | $t$-test ($p$) | | $< .001$ | |

**Table 4.2:** Mean, first and last time-series $CH$ and $SVA$ values for non effective ($Np$) and effective ($Ep$) ball possession episodes. *Note: $t$-test $p$ values refer to $Np$, $Ep$ pairs.*

| | | In Possession ($m^2$) | | Out of Possession ($m^2$) | | I/O ratio | |
|---|---|---|---|---|---|---|---|
| | | $Np$ | $Ep$ | $Np$ | $Ep$ | $Np$ | $Ep$ |
| | Count($n$) | 3357 | 841 | 3357 | 841 | 3357 | 841 |
| **Convex Hull ($CH$)** | | | | | | | |
| $First$ | Mean | 899.4 | 884.2 | 887.8 | 759.9 | 1.14 | 1.96 |
| | SD | 350.8 | 311.9 | 307.8 | 390.7 | 0.72 | 2.54 |
| | $t$-test ($p$) | .252 | | $< .001$ | | $< .001$ | |
| $Mean$ | Mean | 1002.8 | 1025.9 | 815.7 | 696.8 | 1.31 | 1.89 |
| | SD | 318.2 | 231.4 | 233.2 | 292.7 | 0.50 | 1.36 |
| | $t$-test ($p$) | $< .048$ | | $< .001$ | | $< .001$ | |
| $Last$ | Mean | 1011.0 | 1073.0 | 819.2 | 716.3 | 1.49 | 1.93 |
| | SD | 325.1 | 281.8 | 297.8 | 341.6 | 1.72 | 1.51 |
| | $t$-test ($p$) | $< .001$ | | $< .001$ | | $< .001$ | |
| **Sum of Voronoi Areas ($SVA$)** | | | | | | | |
| $First$ | Mean | 3214.9 | 4096.3 | 3953.3 | 3065.9 | 1.09 | 2.78 |
| | SD | 1246.8 | 1604.1 | 1244.9 | 1606.2 | 1.04 | 2.75 |
| | $t$-test ($p$) | $< .001$ | | $< .001$ | | $< .001$ | |
| $Mean$ | Mean | 3590.0 | 4797.2 | 3578.5 | 2374.7 | 1.26 | 2.91 |
| | SD | 1097.9 | 952.3 | 1096.0 | 952.7 | 0.96 | 2.65 |
| | $t$-test ($p$) | $< .001$ | | $< .001$ | | $< .001$ | |
| $Last$ | Mean | 4041.9 | 5517.1 | 3126.4 | 1645.0 | 1.76 | 4.07 |
| | SD | 1190.2 | 606.7 | 1189.0 | 607.9 | 1.51 | 2.32 |
| | $t$-test ($p$) | $< .001$ | | $< .001$ | | $< .001$ | |

**Table 4.3:** $ApEn$ of Convex Hull ($CH$) and Sum of Voronoi Areas ($SVA$) time-series, non effective ($Np$) and effective ($Ep$). *Note: $t$-test $p$ values refer to $Np$, $Ep$ pairs.*

| | | In Possession | | Out of Possession | | I/O ratio | |
|---|---|---|---|---|---|---|---|
| | | $Np$ | $Ep$ | $Np$ | $Ep$ | $Np$ | $Ep$ |
| | Count($n$) | 2666 | 707 | 2666 | 707 | 2666 | 707 |
| $CH$ | Mean | .107 | .106 | .118 | .125 | .124 | .126 |
| | SD | .087 | .074 | .090 | .077 | .097 | .087 |
| | $t$-test ($p$) | .780 | | .083 | | .655 | |
| $SVA$ | Mean | .113 | .086 | .113 | .087 | .113 | .091 |
| | SD | .094 | .081 | .095 | .083 | .094 | .081 |
| | $t$-test ($p$) | $< .001$ | | $< .001$ | | $< .001$ | |
| $CH\ RoC$ | Mean | .793 | .860 | .789 | .842 | .767 | .844 |
| | SD | .243 | .246 | .236 | .244 | .248 | .257 |
| | $t$-test ($p$) | $< .001$ | | $< .001$ | | $< .001$ | |
| $SVA\ RoC$ | Mean | .732 | .766 | .737 | .773 | .675 | .617 |
| | SD | .204 | .207 | .203 | .204 | .194 | .189 |
| | $t$-test ($p$) | $< .001$ | | $< .001$ | | $< .001$ | |

# References


Aarts, Sil, Marjan Van Den Akker, and Bjorn Winkens (2014). “The importance of effect sizes”. In: *European Journal of General Practice* 20.1, pp. 61–64. DOI: 10.3109/13814788.2013.818655.

American Psychological Association (2015). *APA Dictionary of Psychology (2nd Ed.)*

Andrienko, Gennady et al. (2017). *Visual analysis of pressure in football*. Vol. 31. 6, pp. 1793–1839. DOI: 10.1007/s10618-017-0513-2.

Araujo, J et al. (2017). “Ecological cognition : expert decision-making behaviour in sport”. In: *International Review of Sport and Exercise Psychology*.

Araújo, D. and K. Davids (2016). “Team synergies in sport: Theory and measures”. In: *Frontiers in Psychology* 7.SEP, pp. 1–13. DOI: 10.3389/fpsyg.2016.01449Team.

Bartlett, Roger et al. (2012). “Analysing team coordination patterns from player movement trajectories in soccer: Methodological considerations”. In: *International Journal of Performance Analysis in Sport* 12.2, pp. 398–424. DOI: 10.1080/24748668.2012.11868607.

Bauer, Pascal and Gabriel Anzer (2021). “Data-driven detection of counterpressing in professional football”. In: *Data Mining and Knowledge Discovery* 35.5, pp. 2009–2049. DOI: 10.1007/s10618-021-00763-7.

Bourbousson, Jérôme, Carole Sève, and Tim McGarry (2010). “Space-time coordination dynamics in basketball: Part 2. the interaction between the two teams”. In: *Journal of Sports Sciences* 28.3, pp. 349–358. DOI: 10.1080/02640410903503640.

Carling, C., G. Dupont, and F. Le Gall (2011). “The effect of a cold environment on physical activity profiles in elite soccer match-play”. In: *International Journal of Sports Medicine* 32.7, pp. 542–545. DOI: 10.1055/s-0031-1273711.

Carmichael, F. and D. Thomas (2005). “Home-field effect and team performance: evidence from English premiership football”. In: *Journal of sports economics* 6.3, pp. 264–281.

Cessie, Saskia, Jelle J Goeman, and Olaf M Dekkers (2020). “Who is afraid of non-normal data? Choosing between parametric and non-parametric tests”. In: *European journal of endocrinology* 182.2, E1–E3.

Clemente, Filipe M., Micael S. Couceiro, and Fernando M.L. Martins (2012). “Towards a new method to analyze the soccer teams tactical behaviour: Measuring the effective area of play”. In: *Indian Journal of Science and Technology* 5.12, pp. 3792–3801. DOI: 10.17485/ijst/2012/v5i12/30615.

Clemente, Filipe Manuel et al. (2015). “Using network metrics in soccer: A macro-analysis”. In: *Journal of Human Kinetics* 45.1, pp. 123–134. DOI: 10.1515/hukin-2015-0013.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. (2nd ed). Hillsdale: Erlbaum Associates.

Collet, Christian (2013). “The possession game? A comparative analysis of ball retention and team success in European and international football, 2007-2010”. In: *Journal of Sports Sciences* 31.2, pp. 123–136. DOI: 10.1080/02640414.2012.727455.

Correia, Vanda et al. (2011). “Territorial gain dynamics regulates success in attacking sub-phases of team sports”. In: *Psychology of Sport and Exercise* 12.6, pp. 662–669. DOI: 10.1016/j.psychsport.2011.06.001.

Di Salvo, Valter et al. (2006). “Validation of Prozone ®: A new video-based performance analysis system”. In: *International Journal of Performance Analysis in Sport* 6.1, pp. 108–119. DOI: 10.1080/24748668.2006.11868359.

Duarte, R and T Frias (2011). “Collective intelligence: An incursion into the tactical performance of football teams”. In: *Proceedings of the First International Conference in Science and Football*, pp. 15–17.

Folgado, H. et al. (2012). “Length, width and centroid distance as measures of teams tactical performance in youth football”. In: *Eur. J. Sport Sci.* 14.Supple.1, S487–S492. DOI: 10.1080/17461391.2012.730060.

Fonseca, Sofia et al. (2012). “Spatial dynamics of team sports exposed by Voronoi diagrams”. In: *Human Movement Science* 31.6, pp. 1652–1659. DOI: 10.1016/j.humov.2012.04.006.

Frencken, W. and K. Lemmink (2008). “Team kinematics of small-sided soccer games. A systematic approach”. In: *Science and football VI: Proceedings of the 6th World*. Ed. by In T. Reilly & F. Korkusuz (Eds.) September. New York: Routledge, pp. 161–166.

Gesbert, Vincent and Annick Durny (Oct. 2017). “A Case Study of Forms of Sharing in a Highly Interdependent Soccer Team During Competitive Interactions”. In: *Journal of Applied Sport Psychology* 29.4, pp. 466–483. DOI: 10.1080/10413200.2017.1287787.

Goes, F. R. et al. (2020). “Unlocking the potential of big data to support tactical performance analysis in professional soccer: A systematic review”. In: *European Journal of Sport Science* 0.0, pp. 1–16. DOI: 10.1080/17461391.2020.1747552.

González-Rodenas, J. et al. (2020). “Playing tactics, contextual variables and offensive effectiveness in English Premier League soccer matches. A multilevel analysis”. In: *Plos one* 15.2, pp. 1–15. DOI: 10.1371/journal.pone.0226978.

Gréhaigne, J., P. Godbout, and Z. Zera (2011). “How the “ rapport de forces ” evolves in a soccer match : the dynamics of collective”. In: *Rev. Psicol. Deporte* 20, pp. 747–765.

Gréhaigne, Jean Francis, Daniel Bouthier, and Bernard David (1997). “Dynamic-system analysis of opponent relationships in collective actions in soccer”. In: *Journal of Sports Sciences* 15.2, pp. 137–149. DOI: 10.1080/026404197367416.

Hirotsu, Nobuyoshi et al. (2009). “Modeling Tactical Changes of Formation in Association Football as a Zero-Sum Game”. In: *Journal of Quantitative Analysis in Sports* 5.

Hughes, C. (1990). *The winning formula*. Collins.

Hughes, Mike and Ian Franks (2005). “Analysis of passing sequences, shots and goals in soccer”. In: *Journal of Sports Sciences* 23.5, pp. 509–514. DOI: 10.1080/02640410410001716779.

Hughes, Mike and Trevor Lovell (2019). “Transition to attack in elite soccer”. In: *Journal of Human Sport and Exercise* 14.1, pp. 236–253. DOI: 10.14198/jhse.2019.141.20.

Kim, S. (2004). “Voronoi Analysis of a Soccer Game”. In: *Nonlinear Analysis: Modelling and Control* 9.3, pp. 233–240.

Kirk, David and Ann MacPhail (2002). “Teaching Games for Understanding and situated learning: Rethinking the Bunker-Thorpe model”. In: *Journal of Teaching in Physical Education* 21.2, pp. 177–192. DOI: 10.1123/jtpe.21.2.177.

Lago-Peñas, Carlos and Alexandre Dellal (2010). “Ball possession strategies in elite soccer according to the evolution of the match-score: The influence of situational variables”. In: *Journal of Human Kinetics* 25.1, pp. 93–100. DOI: 10.2478/v10078-010-0036-z.

Lopes, A. et al. (2013). “Tracking Multiple Handball Players using Multi-Commodity Network Flow for Assessing Tactical Behavior”. In: *Scientific Conference Women and Handball: Scientific and Practical Approaches*.

Lopes, António et al. (2015). “Using Voronoi diagrams to describe tactical behaviour in invasive team sports: An application in basketball”. In: *Cuadernos de Psicologia del Deporte* 15.1, pp. 123–130. DOI: 10.4321/S1578-84232015000100012.

Low, Benedict, Gabriel Vilas Boas, et al. (2018). “Exploring the effects of deep-defending vs high-press on footballers’ tactical behaviour, physical and physiological performance: A pilot study”. In: *Motriz. Revista de Educacao Fisica* 24.2, pp. 1–7. DOI: 10.1590/S1980-6574201800020009.

Low, Benedict, Robert Rein, et al. (2021). “The porous high-press ? An experimental approach investigating tactical behaviours from two pressing strategies in football”. In: *Journal of Sports Sciences* 39.19, pp. 2199–2210. DOI: 10.1080/02640414.2021.1925424.

Mateus, J. (2005). “In pursuit of an ecological and fractal approach to soccer coaching”. In: *Science and Football V : The Proceedings of the Fifth World Congress on Science and Football,* pp. 561–573.

Mitrotasios, Michalis, Joaquin Gonzalez-rodenas, and Vasilis Armatas (2019). “The creation of goal scoring opportunities in professional soccer . Tactical differences between Spanish La Liga , English Premier League , German Bundesliga and Italian Serie A”. In: *International Journal of Performance Analysis in Sport* 19.3, pp. 452–465. DOI: 10.1080/24748668.2019.1618568.

Moreau, D. et al. (2011). “Growth hormone transgenesis does not influence territorial dominance or growth and survival of first-feeding Atlantic salmon Salmo salar in food-limited stream microcosms”. In: *Journal of Fish Biology* 78.3, pp. 726–740.

Moura, Felipe Arruda et al. (2012). “Quantitative analysis of Brazilian football players’ organisation on the pitch”. In: *Sports Biomechanics* 11.1, pp. 85–96. DOI: 10.1080/14763141.2011.637123.

Perl, Jürgen and Daniel Memmert (2016). “Soccer analyses by means of artificial neural networks, automatic pass recognition and voronoi-cells: An approach of measuring tactical success”. In: *Advances in Intelligent Systems and Computing*. Vol. 392. Springer Verlag, pp. 77–84. DOI: 10.1007/978-3-319-24560-7_10.

Pincus, Sieven M. (1991). “Approximate entropy as a measure of system complexity”. In: *Proceedings of the National Academy of Sciences of the United States of America* 88.6, pp. 2297–2301. DOI: 10.1073/pnas.88.6.2297.

Pratas, J Maria, A Volossovitch, and A Isabel Carita (2018). “Goal scoring in elite male football: A systematic review”. In: *Journal of Human Sport and Exercise* 218.1, pp. 218–230. DOI: 10.14198/jhse.2018.131.19.

Ramos, Ana et al. (2020). “The constraint-led approach to enhancing team synergies in sport - What do we currently know and how can we move forward? A systematic review and meta-analyses”. In: *Psychology of Sport and Exercise* 50.May. DOI: 10.1016/j.psychsport.2020.101754.

Rein, Robert (2016). “Measuring interpersonal coordination – a selection of modern analysis techniques”. In: *Interpersonal Coordination and Performance in Social Systems*. Routledge, Ch. 19 ( 295–311).

Rein, Robert, Dominik Raabe, and Daniel Memmert (Oct. 2017). ““Which pass is better?” Novel approaches to assess passing effectiveness in elite soccer”. In: *Human Movement Science* 55, pp. 172–181. DOI: 10.1016/j.humov.2017.07.010.

Rico-González, Markel et al. (Apr. 2020). *The use of technology and sampling frequency to measure variables of tactical positioning in team sports: a systematic review*. DOI: 10.1080/15438627.2019.1660879.

Santana, Juliana (2011). “Representação da área de responsabilidade de jogadores de futebol através do Diagrama de Voronoi”. PhD thesis. Universidade Estadual de Campinas.

Sarmento, Hugo et al. (2014). “Match analysis in football: a systematic review”. In: *Journal of Sports Sciences* 32.20, pp. 1831–1843. DOI: 10.1080/02640414.2014.898852.

Sawilowsky, Shlomo S. (2009). “New Effect Size Rules of Thumb”. In: *Journal of Modern Applied Statistical Methods* 8.2, pp. 597–599. DOI: 10.22237/jmasm/1257035100.

Spencer, Bart, Matthew Hawkey, and Sam Robertson (2019). “Using contextual player movement and spatial control to analyse player passing trends in football”. In: *Barça sports analytics summit*, pp. 1–12.

STATS (2019). *STATS Playing Styles, Definitions Manual*.

Takeuchi, T. (2011). “Body morphologies shape territorial dominance in the satyrine butterfly Lethe diana”. In: *Behavioral Ecology and Sociobiology* 65.8, pp. 1559–1566.

Taki, Tsuyoshi and Jun ichi Hasegawa (2000). “Visualization of dominant region in team games and its application to teamwork analysis”. In: *Proceedings of Computer Graphics International Conference, CGI*, pp. 227–235. DOI: 10.1109/cgi.2000.852338.

Teodorescu, L. (1984). *Problemas de teoria e metodologia nos jogos desportivos*. Ed. by Ed. Horizonte. Lisboa.

Thorpe, R., D. Bunker, and L. Almond (1986). *Rethinking games teaching*. Department of Physical Education and Sport Science. Loughborough : University of technology.

Timmerman, Ewout and Damian Farrow (2017). “The effect of manipulating task constraints on game performance in youth field hockey”. In: *International Journal of Sports Science & Coaching* 12.5, pp. 588–594. DOI: 10.1177/1747954117727659.

Ueda, Fumiya, Honda Masaaki, and Horino Hiroyuki (2014). “The Causal Relationship between Dominant Region and Offense- Defense Performance - Focusing on the Time of Ball Acquisition”. In: *Football Science* 11, pp. 1–17.

Vilar, Luís et al. (2013). “Science of winning soccer: Emergent pattern-forming dynamics in association football”. In: *Journal of Systems Science and Complexity* 26.1, pp. 73–84. DOI: 10.1007/s11424-013-2286-z.

Yoshimura, M. (2003). “A Study on Tactics of Attack in Football Game - The training for effective attacks”. In: *Sports Science Jyuntendo Journal of Health and Sports* 7, pp. 48–61.

## Chapter 5

# A dynamic method based on Voronoi-diagrams to assess the collective functional degrees of freedom of team passing behaviour in high-performance football

Caldeira, N., Lopes, R.J., Fernandes, D. & Araújo, D. (Under revision: PLoS ONE)

## Abstract

In high-performance football contexts, coaches' ability to communicate tactical knowledge is key. In this context, it is urgent to create methods that can blur the abyss that sometimes separates quantitative data from the practical (qualitative) knowledge that can be extracted from them. Following an ecological dynamics approach, the present paper proposes a method to bridge this gap regarding a parameter correlated with successful overall performances: ball possession. Capturing the team's collective synergies into *functional degrees of freedom* (fDOF) from the player's positional quantitative data, our method aims to translate teams' dynamic passing affordances. (i.e., opportunities for players to interact through passing) to coaches' qualitative language. For a player to perform a pass, the team must offer *possibilities for pass* reception to the ball carrier, at the effective play-space (EPS). These *possibilities* can be assessed as collective fDOF, that were obtained dividing the EPS in twelve dynamic zones, computed as Voronoi cells around the match centroid (defining interior and exterior regions of the EPS). The proposed method was applied to positional data of a high-performance football match (French Ligue 1) at different time scales: *a)* instant analysis; *b)* successive passing instants (during a play); *c)* successive periods, such as halves of a match. The results obtained indicate that the proposed method can be applied in different scenarios and combined with other contextual data to qualitatively substantiate the tactical knowledge of coaches on the performance of their teams.



## Keywords

Players' distribution, Tactical performance, Functional Degrees of Freedom, Effective Play-Space, Voronoi diagrams

## 5.1 Introduction

In high-performance football contexts, is key the ability of coaches' to communicate their tactical knowledge with their players and support staff (Occhino, Mallett, and Rynne, 2013). In this realm, despite the academic interest afforded to sports science research, its translation to the daily practice of elite football coaches is still limited (Fullagar et al., 2019). This can be possibly explained by the "lack of specific football knowledge of scientists" and the "poor applicability of sports science in practice" (Brink et al., 2018, p150). This perception about sports science may justify why high-performance coaches usually get knowledge from other coaches, or from coaching clinics and seminars, and not from sports scientists or their written work (Reade, Rodgers, and Spriggs, 2008). Is crucial to bridge this gap, approaching the research methods with the language used by football coaches in their daily practice to communicate with their players. In fact, more than an essentially quantitative approach (using statistic methods), coaches' language demands extracting essentially qualitative tactical insights from the game (even if supported in numbers).

This need is especially important in tactical terms when coaches aim to develop players' ability to play together and interact with others, to increase the overall team's capacity to perform. In this context, players' tactical ability to cooperate with their teammates, can be supported by several general pedagogical "principles of play" (Wade, 1998). These principles are guidelines to establish "inter-players' relationships in a given space and time" (Clemente et al., 2014, p665). Thus, through practice (Silva, Vilar, et al., 2016) players develop their ability to coordinate with teammates in the game context (Barnabé et al., 2016), becoming attuned to collectively join together to protect their goal area (defending), and to spread or disperse to attack the opponent's goal area (Ricardo Duarte et al., 2013). However, at the high-performance level, it is not enough to simply follow these simple guidelines (Clemente et al., 2014, p665). The relevant issue is how team players effectively disperse or assemble in different match sub-phases (e.g., when the team is *in* or *out* of ball possession). To understand how team players disperse as a whole in a coordinated way, in this paper we developed and tested a method to dynamically assess players' distribution on the pitch as collective *functional degrees of freedom* (fDOF). From our point of view, the idea of fDOF can constitute a simple data-based language that facilitates coaches tactical communication of more complex insights about the functional effects that result from players' interactions (synergies).

From the many collective tasks where players need to synergistically cooperate, in this article, we focused on the "in possession" game sub-phase, as teams' ability to maintain the ball possession is highly correlated with successful overall performances (Pina, Paulo, and Duarte Araújo, 2017). In these sub-phases, high-performance teams need to coordinate their players' distribution on the pitch, forming global team spatial configurations (i.e., pattern, or the arrangement of elements in a particular form, figure, or combination). In each moment, an effective team configuration allows occupation of the pitch that maximizes the possibilities of interaction between their players (later in the paper quantified as fDOF of the team as a whole). We argue that these possibilities of interaction emerge from the players' spatial distribution on the pitch during the "in-possession phase" and are related to teams' ability to achieve offensive and defensive aims. In fact, by enhancing the opportunities to pass, teams can offensively approach the opponent's goal area, aiming to shoot and score. Furthermore, by maintaining the ball for longer periods of time, the "in-possession" team can also pursue defensive purposes preventing the opponent to attack their own goal. In addition, the in-possession teams' spatial configuration is related to the team's global balance, being also important to the teams' performance during the brief transition periods immediately after the ball loss, as it impacts the team's ability to stop the opponent's counterattack.

Therefore, in the game landscape (Gómez-Jordana et al., 2019), teams' configurations express interpersonal linkages, a property of team synergies, i.e. the "specific contribution of each element to a group task" (D. Araújo and K. Davids, 2016). In fact, although team configurations are constrained by the design previously developed by the coach (e.g., players' role in a given team formation), the game is dynamic and the specific position on the pitch of each player at a given moment cannot be rigidly defined by this design (McLean et al., 2018). Consequently, the instantaneous team configuration is strongly influenced by the team's "reciprocal compensation" (D. Araújo and K. Davids, 2016), i.e., "the ability of one component of a synergy to react to changes in others" (Riley et al., 2011, p1). Therefore, as in other social systems, football players compensate each other during a game (via their pitch displacements), to achieve or maintain an effective overall configuration for their team. Considering a football team as a dynamic system (Keith Davids, Duarte Araújo, and Shuttleworth, 2005), the team's coordination and collective performance are constrained by the possibilities of interaction between its elements (players) (i.e., their collective degrees of freedom). Thus, it is important to situate the degrees of freedom (DOF) concept and how it can be understood at the team level, when the purpose is to tactically communicate in the context of high-performance football.

### 5.1.1 Football team's functional degrees of freedom

The degrees of freedom (DOF) concept has very wide use in several different types of systems, from the molecular scale (Stefan, Kob, and Schilling, 1997) to the study of social networks (Shahal et al., 2020). In human movement science, this concept is particularly relevant as it has been used to understand coordinated behaviour (Bernstein, 1967). In a nutshell, DOF can be defined as "the number of variables that can be independently varied" (Li, 2006, p303). Looking at the "in-possession team" and their players' possibilities of interaction via ball passing, is easy to recognize that the ball carrier has a maximum of ten other possible teammates to pass the ball, i.e., ten DOF. However, we argue that due to game constraints it is not always possible to have ten *passing possibilities*, i.e., *passsing affordances* (Gibson, 1979). Therefore, in a given team collective action (e.g., maintaining the ball possession), some DOF may not be available, i.e., may be constrained. Therefore, it is important to underline the relevance of the *functional* degrees of freedom (fDOF) concept, as the remaining DOF that can independently vary during a particular action due to the imposition of task-specific constraints on the original DOF (Li, 2006). From this point of view, the number of actual interaction possibilities between the players of a given "in-possession" team emerge from the game's constraints and can be quantitatively assessed by their collective fDOF (Pennestri, Cavacece, and Vita, 2005).

Constraints specific to football match behaviour arise from game rules, such as the spatial location where the match can happen. For the match dynamics, a constraint such as the off-side rule drastically reduces the space available on the pitch and the possibilities of interaction among players. This means that, although there is a maximum of ten passing possibilities for the ball carrier, an offside player does not offer a functional possibility for passing in a football match (Andrienko et al., 2017). That is, albeit the team's degrees of freedom (DOF) are maintained, the team's functional degrees of freedom (fDOF) are reduced to nine when one player is offside. In addition to game rules, the team's instantaneous configuration on the pitch also constrains their fDOF. Notably, when two teammates of the ball carrier are near each other, i.e., in the same match space, one player can have a position that is redundant to the other player thus reducing the passing interaction possibilities (fDOF) of the team (Pennestri, Cavacece, and Vita, 2005). This redundancy is a situation of great practical relevance in coaches' game interpretation, as a single player of the opponent team can nullify two players of the ball "in-possession" team.

The global team configuration for pass affordances should be understood in relation to its effectiveness, which varies according to the local context around the ball carrier (Cakmak, Uzun, and Delibas, 2018). From an ecological dynamics perspective, gaps are constantly changing in the game landscape due to the positions of opponents and teammates (Gómez-Jordana et al., 2019). This implies that the "ability to see an opening for a pass" (Gudmundsson and Wolle, 2014, p17) is an affordance in which perception is constrained according to interpersonal distance, speed and angles among players (Travassos et al., 2012). Thus, the decision to pass is not made exclusively by the ball carrier (Araujo et al., 2017), but it emerges under the constraints of the match, where the affordances offered by players without the ball are part and parcel of the decision-making behaviour of the ball possession team (J. Fernandez and Bornn, 2018; Narizuka, Yamazaki, and Takizawa, 2021). Passing opportunities for a team are *shared* affordances (Silva, Garganta, et al., 2013), where players are attuned to collective actions that foster these opportunities for the ball carrier's actions. For example, when a ball carrier teammate is *hidden* behind an opponent he is not offering a passing affordance. Therefore, spatio-temporal data analysis has the potential to measure players' decision-making behaviour by capturing the set of passing affordances for the ball carrier in a given team configuration. This approach operationalizes the interpersonal linkages and reciprocal compensation properties of team synergies (D. Araújo and K. Davids, 2016; Carrilho et al., 2020). Moreover, several metrics have been proposed to assess *passable areas* (Gudmundsson and Wolle, 2014; Gómez-Jordana et al., 2019) or players' *space control* (Rein and Memmert, 2016; Rein, Raabe, and Memmert, 2017; J. Fernandez and Bornn, 2018).

In the current paper, we propose the use of metrics based on Voronoi diagrams to ecologically (functionally) capture the players' distribution on the pitch and the team's global fDOF, in order to facilitate coaches' interpretation of the game content and inherent communication (e.g., with players).

### 5.1.2 The assessment of ecologically defined players' distribution on the pitch

When in ball possession, teams tend to expand and increase the distance between players (Moura et al., 2012; Ric et al., 2016), captured by their dispersion on the pitch (Bartlett et al., 2012; Merlin et al., 2020). At a local level, Passos and colleagues Passos, Duarte Araújo, and Keith Davids, 2013, p5 demonstrated, in invasion team sports, that the dispersion around the ball carrier "is typically achieved by acquiring a geometric form similar to (but not fixed in) a diamond-shaped structure". On the other hand, at the global level, McLean and colleagues McLean et al., 2018 observed that team's formation influences their passing network. Here, the passes network was built from successful passes actually made during a large time period (e.g., an entire match) and not from the passing affordances (or available fDOF) in a given instant. In this paper, we posit that the quantification of passing fDOF should consider the players' distribution on the pitch at the *glocal* level (Robertson, 1995). That is, regarding the dynamic pitch distribution of all players (global) and referenced to the ball carrier (local), in different time scales. Consequently, it is necessary to review the traditional approach to assess players' distribution on the field, based in a division of the pitch in fixed zones. In these traditional models, players' distribution on the pitch is analysed via *point pattern analysis* (PPA) and quadrant methods (Boots and Getis, 2020), using a grid that divides the pith in a different number of longitudinal and lateral zones. For example, a model that divides the pitch in 18 zones was used in several types of research (Jonsson et al., 2003; Herold et al., 2019; J. Kim et al., 2019).

However, PPA quadrant methods does not necessarily impose fixed zones, opening doors also to more dynamic models that can be created with the purpose of capturing team behaviour addressing the equally dynamic nature of the game (Keith Davids, Duarte Araújo, and Shuttleworth, 2005). For example, nowadays in high-level football matches, the teams' compactness is increasing (Okihara et al., 2004) with all outfield players closer to each other, frequently occupying an area smaller than 20% of the pitch (Moura et al., 2012). This compactness implies that previously determined fixed zones, that divide the pitch into rigid squares, hardly capture players' distribution on the field according to match dynamics.

A dynamic way to capture players' dispersion is using methods to detail players' distribution on the effective play-space (EPS), defined by the convex hull of all pitch players of both teams (J.F. Gréhaigne, Mahut, and A. Fernandez, 2001). Vilar and colleagues Vilar et al., 2013 divided the EPS into seven zones to dynamically capture the number of teammates in a given space and compare it with the number of opponents in the same physical space. Vilar and colleagues Vilar et al., 2013 computed their seven zones by the division of the relative length and relative width of the EPS. This approach is thus sensitive to the variations of the EPS dimensions and shape, following teams' dynamics in a match. However, such zones are easily influenced by the positioning of an isolated player. Moreover, the discrimination between interior and exterior positions is seriously impaired by considering that there is a single interior centre-middle sub-area with a fixed relative dimension and shape (50% of the longitudinal and lateral dimension of the convex hull) and not the ongoing interactions between players (teammates and opponents).

In fact, to capture with adequate detail the teams' distribution of players in the EPS and their fDOF, it is necessary to have greater plasticity and granularity in the EPS division. To achieve this, we propose to capture players' fine-grained distribution on the pitch by computing Voronoi diagrams (VD) using the position of all players over time. Here, VD are used not only to measure the area of the Voronoi cell of each player (S. Kim, 2004; Fonseca et al., 2012; Perl and Memmert, 2016), but also players' distribution on the pitch in interior and exterior EPS dynamic zones. That is, considering the dynamics of both teams in the context of the match.

For the team with ball possession, this distinction between the interior and exterior zones of the EPS facilitates the understanding of the possibilities for passing for the ball carrier. For example, Rosén (Rosén, 2015) showed that two wing players in opposite corridors rarely pass the ball to each other, using instead intermediate players in the interior of the EPS to switch the attack corridor. For capturing such dispersion and assembly, it is necessary to consider:

1. A reference point located at the centroid of the game i.e., the *geometrical centre* of all outfield players. In fact, as in other complex systems, players do not randomly disperse in the pitch of play but act in a coordinated way around attractors with the consequent changes in the geometrical centre of the match (D. Araújo, K. Davids, et al., 2004; Duarte and Frias, 2011; Gorman et al., 2017). The centroid of the game captures globally all players' positions, and unlike measures of length and width, it dilutes major movements from a single player.

2. A dynamic and plastic division of the EPS based on Voronoi diagrams (VD). In fact, VD captures the spatial interaction between players defining cells with adaptative shape and size (Rein, Raabe, and Memmert, 2017). Additionally, by identifying interior and exterior zones, VD and players' pitch distribution can be understood according to the game dynamics.

In the current paper we argued that, through the assessment of players' distribution on the pitch, the teams' fDOF can capture the interpersonal linkages and reciprocal compensation properties of team synergies, which support the perception of passing affordances for the ball carrier. This information is highly relevant to complement football coaches' perception (Brink et al., 2018).

## 5.2 Materials and Methods

### 5.2.1 Data sources

Positional and event data from 20 games of the main French Football League (Ligue 1), held in the 2019-2020 season, was explored to build this method. In the present article, as a proof-of-concept, we presented illustrative results extracted from one of these matches. Data was obtained and processed by the company STATS© using semi-automatic tracking systems with a sampling frequency of 10Hz (as validated by (Di Salvo et al., 2006)). The system provides the position of all 22 players plus the ball in a two-dimensional coordinate system (longitudinal and lateral) over time. Positional data were synchronized by STATS with two additional event sources: the respective match events (i.e., ball touches, passes, shots, goals, etc.) and both teams' ball possessions (i.e., the time instants of the ball recovery and loss, in what constitutes a ”possession episode”).

### 5.2.2 Data processing

The focus of this study was on the dynamics of ball possession and affordances for passing. Thus, the players' distribution on the pitch was considered only in the samples when there was a passing event made by an outfield player, regardless of whether it enabled the continuity of ball possession (when the next player to touch the ball was from the same team) or not. Figure 5.1 illustrates the results obtained, for one-time frame, from the three data processing steps (described in detail in the remainder of this section):

1. Calculation of the match and teams' centroid (represented in Figure 5.1 as black, blue and red crosses, these last ones are one for each team), and the effective play-space (EPS) for the match (dashed yellow polygon), in possession team (dashed red polygon) and out of possession team (dashed blue polygon).

2. Computation of the Voronoi diagram composed of the cells for each player (red and blue polygons). As described later, the EPS was divided into ”interior” (white shaded in Figure 5.1) and ”exterior regions”.

3. Division of the effective play-space (EPS) in a total of twelve dynamic zones:

   (a) the ”interior region” of the EPS in four zones (quadrants) (divided by the yellow dashed lines of Figure 5.1);

   (b) the ”exterior region” of the EPS in eight zones (octants) (divided by the white dotted lines of Figure 5.1).

#### Match centroid

The match centroid for each frame was calculated as the average value for each pair of coordinates (longitudinal and lateral) of all outfield players from both teams (Goalkeepers were not considered), i.e., it corresponds to the *geometric centre* of both teams' all outfield players (Silva, Ricardo Duarte, et al., 2014). The teams' centroids were computed in a similar way but considering only the outfield players of each team (Frencken et al., 2011). The match effective play-space (EPS) was defined by the convex hull of all outfield players (i.e., not considering the goalkeepers) from both teams, as proposed by Moura and colleagues Moura et al., 2012. The effective play-space for the in possession and the out of possession teams was defined by the convex hull of their outfield players (J.F. Gréhaigne, Mahut, and A. Fernandez, 2001). For the purposes of this paper, only the match effective play-space (EPS) and match centroid were used.

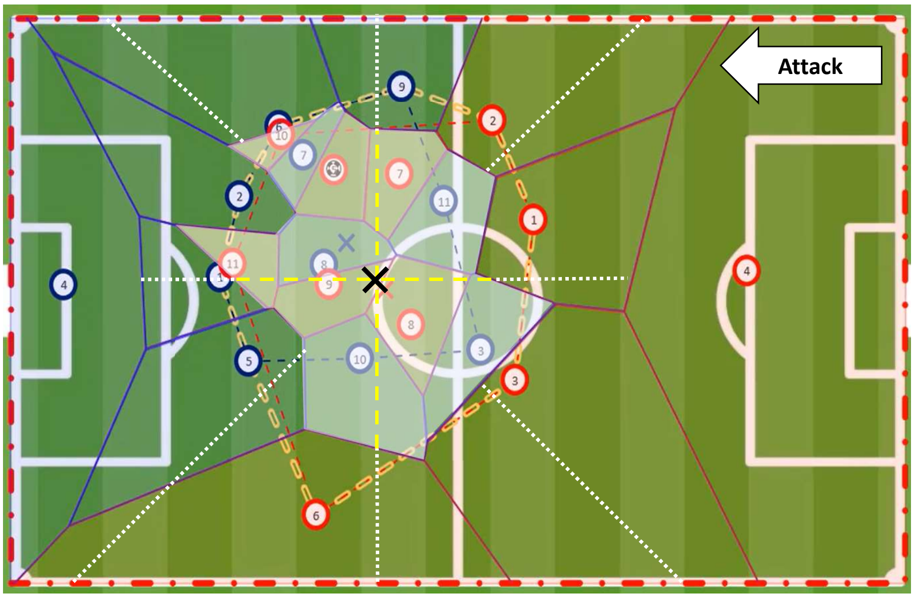



**Figure 5.1:** An example of the division of the EPS in a set of 12 dynamic zones, using the match centroid and Voronoi diagrams for one frame. *Note: Voronoi diagrams with the cells of each player identified by a number. In the diagram is highlighted: a) the match centroid (black cross); b) the teams' centroids (red and blue crosses); c) the match effective play-space (dashed yellow polygon); d) teams' convex hull (blue and red dashed polygons)*

### Voronoi Diagrams

Voronoi diagrams (VD) were calculated using the process described in (S. Kim, 2004). In a VD, the Voronoi cell area (VA) is defined by "all spatial points that are nearer to the player to whom that cell is allocated than to the other players" (D. Araújo and K. Davids, 2016, p9). As shown in Figure 5.1, the VD also identify the players' relative position in two possible types of regions: i) *exterior* (when the player's cell contacts the pitch outlines or the goalkeepers' cells); ii) *interior* (otherwise). Goalkeepers' cells are not included in any of these two types of zones (as they are not part of the EPS).

### Division of the effective play-space (EPS) in twelve dynamic zones

The effective play-space was divided into twelve zones of changing shape and size, based on the players' distribution on the pitch at each time frame. This process was based on two key principles: adaptive spatial reference point (the match centroid) and the delimitation of spatial relationships between players (captured in the Voronoi diagram). As represented in Figure 5.2b, the EPS was schematically divided in *interior* (white) and *exterior* (blue) regions around the match centroid. The interior and exterior regions were respectively subdivided into four quadrants of 90° (zones 5 to 8) and eight octants of 45° (zones 1 to 4 and 9 to 12), resulting in a total of twelve zones for each team. Each of the outfield player's Voronoi cell was tagged with the corresponding zone according to two criteria:

1. If the player's Voronoi cell contact with the pitch outlines or the goalkeepers' Voronoi cells it is classified as an "exterior zone", being classified as an "interior zone" if not;
2. player's angle to the match centroid (measured in degrees, and taking the reference of the "attack direction"), that defines the zone where the player was in a division by quadrant (interior EPS region)

or octant (exterior EPS region).

Figure 5.2a illustrates the results of applying this process to a particular match time frame. It is important to note that the actual shape and size of a particular zone resulted from merging the Voronoi cells from that zone. Actually, a zone can have a zero area if none of the players meets that zone criterion (e.g., Zone 4 in Figure 5.2a).

The importance of the schematic representation in Figure 5.2 is twofold: to operationalise the division of the EPS as described previously, and as an abstract representation of the EPS. Both contributions are used in the remainder of this paper, notably the latter for expressing the application of this process to real match data.

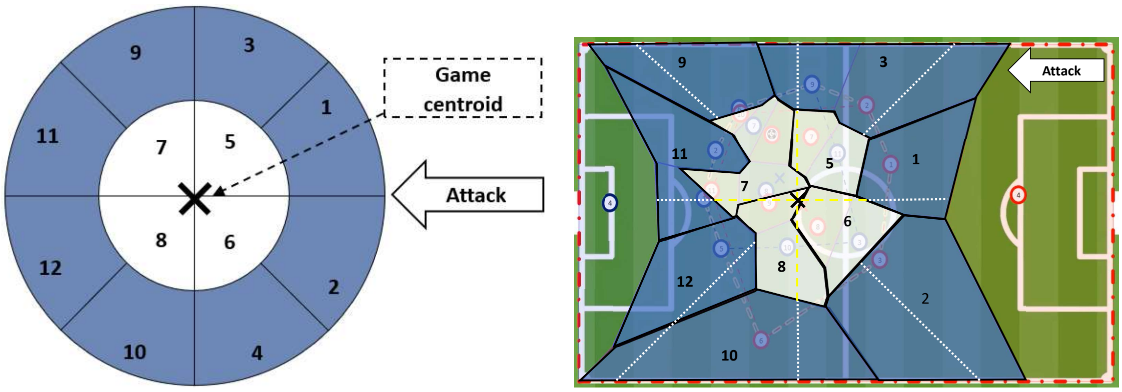
#### Computation of teams' fDOF

The twelve zones (the interior quadrants and the exterior octants) were used to assess the presence of players in each zone, and thus describe the distribution of players of each team in the EPS. In the case of the team in ball possession, this enables to quantify the possibilities for a pass to each zone using the following procedure: a) identify the ball carrier's zone, and b) identify the zones occupied by at least one of his teammates. Furthermore, the functional degrees of freedom (fDOF) of the ball possession team were obtained by counting the number of zones occupied by one or more teammates of the ball carrier, i.e., a fDOF exists when a given zone is occupied by ball carrier teammates. Consequently, two or more players of the same team in the same zone are considered as redundant for the same fDOF. Given these operationalizations, the highest number of passing possibilities for the team in possession was obtained by a distribution of players that guarantees the highest number of fDOF.

#### Computation of teams' zonal balance

In addition to the fDOF, the zonal balance/imbalance between the two teams is also relevant for assessing the opportunities for action (e.g., passing affordances). In this context, the twelve zone tags have a meaning that depends on the team's attacking perspective. Figure 5.3 illustrates how each team ("in" and "out of" possession) uses different tags for the same physical space (Tenga, Mortensholm, and O'Donoghue, 2017), allowing the calculation of the zonal balance/imbalance between opponents. For ease of exposition, the diagrams in Figure 5.3 and the following are rotated relative to that in Figure 5.2 (vertically opposite goalposts).

Considering the attacking direction of each team, it is possible to distinguish more *defensive* (behind the match centroid, zones 1 to 6,) and more *offensive* zones of the EPS (in front of the game's centroid, zones 7 to 12). Similarly, using the imaginary longitudinal line crossing the match centroid, the EPS zones can be classified as *left* (odd tag zones) and *right* side (even tag zones).




**(a)** EPS zones (scheme)

**(b)** EPS zones (illustrative example)

**Figure 5.2:** Division of the EPS into twelve zones: schematic representation (a) and illustrative example (b).

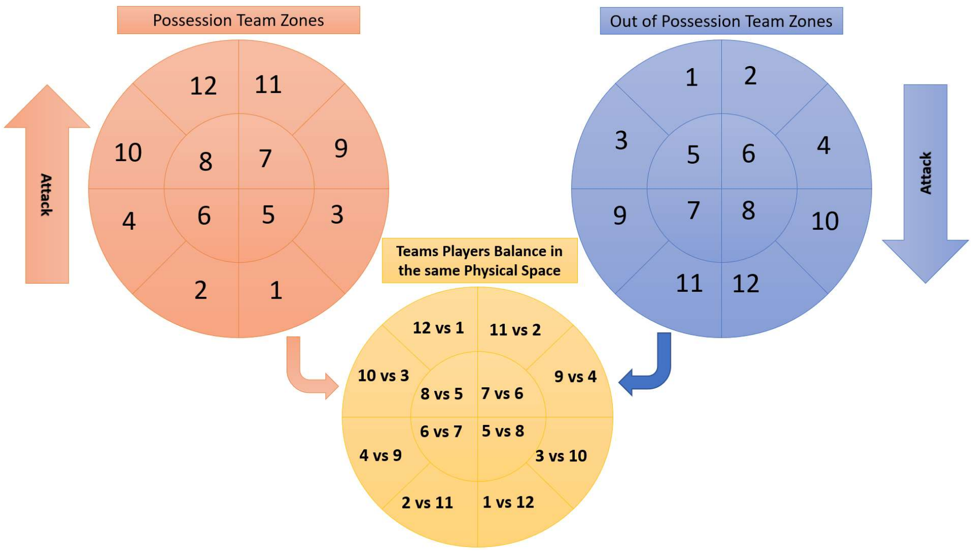



**Figure 5.3:** Assessing the teams' zonal balance

### Analysis in different time scales

[Analysis in different time scales] The previous methods were used in different time scales (i.e., a single moment, two different moments, intervals of time), capturing the distribution of the players of a team on the pitch, in a certain instant of time ($t$), to analyse how that distribution can affect teams' fDOF and teams' zonal balance. As it can be applied to different relevant moments of the match, in this article we selected only the instants corresponding to passing events. An example of applying the analysis to a single pass instant is shown in the first results of sub-section *"Single instant analysis"*. On the other hand, the method also allows to perform a differential analysis between two instants (e.g., comparing two consecutive passes, as exemplified in sub-section *"Two successive passing events analysis"*). Finally, the proposed method allows the observation of longer periods of time, through the analysis of the patterns emerging from an interval (e.g., to compare the differences between the two halves of a match, as exemplified in sub-section *Successive periods analysis: halves of a match*).

## 5.3 Results

In this section, our purpose is to demonstrate how the proposed method, presented in the previous section, can support a tactical description about players' interactions during a football match. For this purpose, more than use deep statistical methods, this section illustrates in different time scales the functional effects (synergies) that emerge from these players' interactions in a match context. Using positional and event data from one real high-performance football match, in the following sections we exemplify how the assessment of team's functional degrees of freedom (fDOF) and team's zonal balance can be used to understand players' distribution on the pitch at different time scales: a) single instant analysis (see 5.3.1); b) successive passing instants (during a play, see 5.3.2); c) successive periods, such as the halves of one match (see 5.3.3).

### 5.3.1 Single instant analysis

The illustrative example in Figure 5.4 for the assessment of the team's functional degrees of freedom (fDOF) and team's zonal balance at a particular instant, is taken from a passing event in the sample match (pass number 68, at $t = 449.6s$). Figure 5.4 is obtained mainly from the schematic representation proposed in Figures 5.2 and 5.3 and populated with the team's fDOF, teams' zonal balance and other contextual information that we set for such representations.

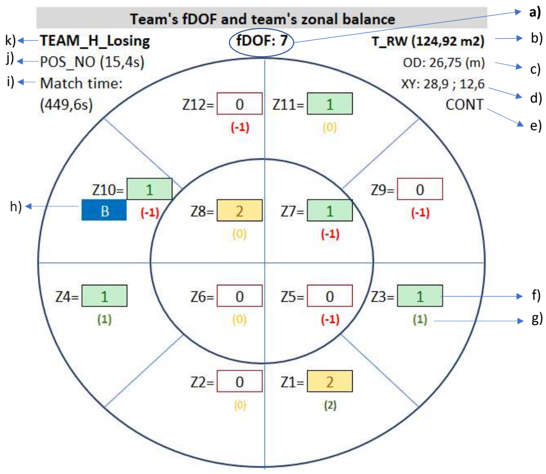



**Figure 5.4:** Team's fDOF and team's zonal balance during a pass event ($t = 449.6s$) *Note: a) Number of the in-possession team's functional degrees of freedom (fDOF, i.e., the number of quadrants and octants that are not empty); b) Identification of the player with the ball, her/his tactical mission (in this case right winger, RW) and her/his Voronoi cell Area ($m^2$); c) Offensive Distance (OD) to the opponent's goal (meters); d) Ball carrier coordinates (longitudinal, x and lateral, y); e) Pass with (CONT) or without (NO CONT) continuity; f) Number of team players in each zone, where $0 \equiv$ White, $1 \equiv$ Green, $2 \equiv$ Yellow and $\geq 3 \equiv$ Red; g) Numerical balance between teams in that zone, where $< 0 \equiv$ Red; $0 \equiv$ Yellow; $> 0 \equiv$ Green; h) Number of the pass event in the match; i) Zone where is the Ball (ball carrier); j) Identification of the instant in the match (seconds); k) Possession episode (PE) with (YES) or without (NO) a finishing event (and the duration of the PE, in seconds); l) Identification of the Team, the venue context (Home or Away) and the current result (draw, winning or losing).*

The information displayed in Figure 5.4 enables reading that particular moment in the match from the global contextual constraints of the match, at the time of the passing opportunities for the ball carrier (i.e., their passing affordances), namely: the team's fDOF, the players' distribution on the EPS twelve zones and corresponding team's zonal balance. An example of such reading, focusing on the possession team and ball carrier, could be:

- The possession team (H) had seven fDOF. This corresponds to the number of occupied EPS zones, i.e., zones where the possession team had at least one player (the number of players is indicated by the colour scheme: $0 \equiv$ White, $1 \equiv$ Green, $2 \equiv$ Yellow and $\geq 3 \equiv$ Red).
- For the possession team (H), only two zones (Z1 and Z8, in yellow) had redundant players.
- The numerical balance information indicates that the ball possession team did not achieve local numerical superiority in any physical space around the ball carrier in the offensive half of the EPS. (Zonal balance is represented with the colour scheme: $< 0 \equiv$ Red; $0 \equiv$ Yellow; $> 0 \equiv$ Green).
- The ball carrier, situated in Z10, only had a passing possibility without opposition in the defensive half of the EPS, in this case in octant Z4.

This information can be further interpreted from a global tactical perspective valuable for practitioners (e.g., coaches). In fact, when we analysed the fDOF of the teams in possession it is clear how difficult it is to achieve the highest collective coordination at all match instants. In a clear example of the need for reciprocal compensation inside a team, in the instant illustrated by Figure 5.4 the following can be observed:

- The ball carrier was a Right Winger (RW) who was momentarily on the left of the EPS, already in the last offensive third (26,75 meters from the centre of the goal).
- Because he was on the opposite side of his starting position in the game, there was a need for the team to compensate in order to maintain as many degrees of freedom as possible.
- In this case, the team managed to keep seven fDOF at that moment, as it had more than one player in just two EPS zones (Z1 and Z8).
- As the ball carrier was an outfield player and, therefore, the ball was inside the EPS, the possession team had a distribution of its players that approached the maximum possible of fDOF (9). This would be an achievable fDOF number, if one of the players from Z8 moved to Z12 looking to explore the space behind the opponent's defensive line, for example, or if one of the two players who were in Z1 was more to the left, in Z2.
- In this last case, one of these two players (central backs) was one more option to the ball carrier to pass the ball if he moved to the left of the EPS. If both Z1 and Z2 were occupied, the free EPS zones to be explored by the opponent through a counterattack would be reduced. However, in a collective organization based on the zone defence principles (J. Gréhaigne, Godbout, and Zera, 2011; T. Frias and R. Duarte, 2014), it could make more sense for the two central defenders to be one in Z1 and the other in Z2, the presence of an opponent in the interior of the EPS (Z5) may have justified the attraction of these two players into Z1.

### 5.3.2 Two successive passing events analysis

The same method also can be used for capturing two successive passing events. Figure 5.5 considers two successive events (passes) from a possession team (H) that is momentarily losing.

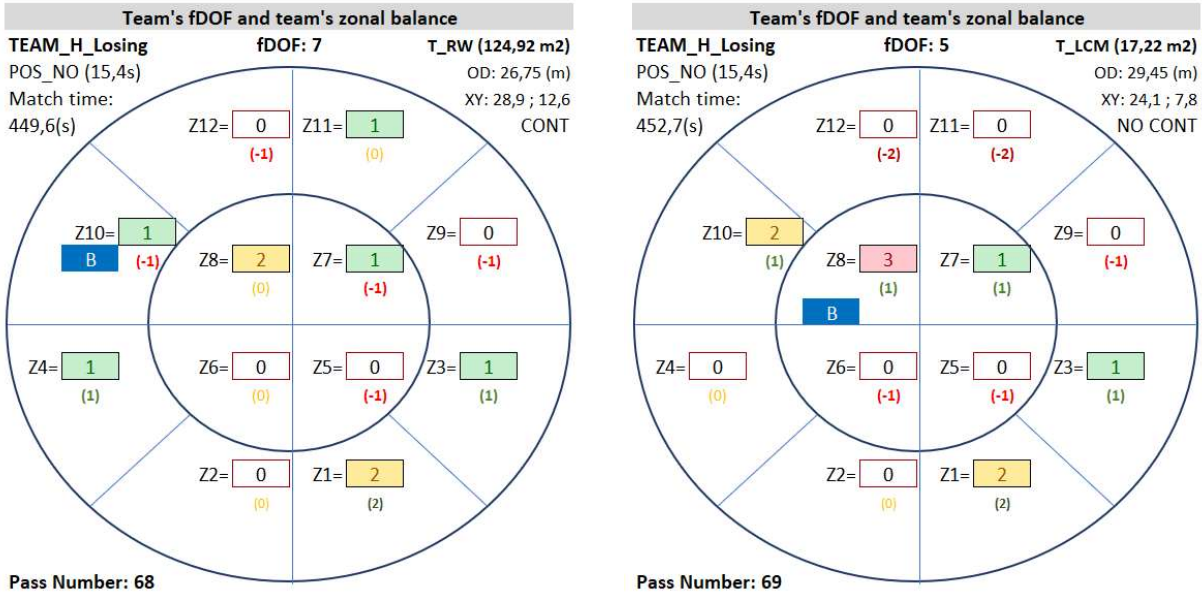



**Figure 5.5:** Team's fDOF and team's zonal balance, dynamics between two passing events (Pass 68 at $t = 449.6s$ and Pass 69 at $t = 452.7s$) (see text for details)

The results illustrated in Figure 5.5 enable reading the match changes in the following way:

- In the instant $t = 449.6s$, the ball is passed from one exterior zone of the EPS (octant Z10), with the ball carrier at $26.75$ meters of the centre of the opposite goal.
- The player with the ball, a Right Winger (RW) that is on the left in this play, could pass the ball to seven other zones of the EPS, as the pass affordances of his outfield teammates allowed that number of fDOF.
- However, in that pass number 68, the ball carrier passed the ball to the interior of the EPS, for a teammate (a left centre midfielder, LCM) in zone 8 (quadrant Z8) of the scheme.
- Approximately three seconds later ($t = 452.7s$), when the next pass (69) was performed by the Left Centre Midfielder (LCM), it was possible to observe the presence of three teammates in the single zone of the ball carrier (quadrant Z8). Players' agglomeration in quadrant Z8 led to seven empty EPS zones, implying the reduction of the possession team's fDOF to only five.

These observations can foster a tactical understanding of the match dynamics, namely:

- From one passing instant to the next, possession team (H) players' distribution implied the reduction of the respective number of EPS occupied zones (i.e., the reduction of its fDOF from seven to five). In the instant B of Figure 5.5, is evident how the lack of more dispersed passing options through all EPS possibly contributed to the ball loss. The reduction of fDOF also brought an agglomeration around the ball carrier, with 3 other teammates in the same EPS zone (Z8). This circumstance explained the strong decrease in the ball carrier's Voronoi area (only about $17m^2$), expressing the small space to execute the pass conveniently.

- Thus, despite the numerical superiority of the possession team in the zone of the ball (+1), the reduction of fDOF and the available space of the ball carrier, probably led to the loss of ball possession (not allowing the team H to explore other EPS zones). Additionally, it made room for a potentially dangerous transition of the opponent team, judging by the number of unoccupied zones in the defensive part of the EPS.

From this example, it is possible to speculate that attaining and sustaining the highest number of fDOF is a collective challenge for a team in possession that can underpin the team's global performance (both offensively and defensively).

### 5.3.3 Successive periods analysis: halves of a match

To visualize the patterns of the team's players' distribution on the pitch during a period, data can be studied as a temporal series, namely, by populating the twelve zones' representation of the pitch with statistical data. For example, the pie charts in Figure 5.6 show the relative frequency (percentage) of passing instants during half of a match and the respective number of players in each zone of the EPS (0 ≡ blue; 1 ≡ orange; 2 ≡ grey; 3 ≡ yellow, > 4 ≡ light blue). Additionally, Figure 5.6 presents the percentage of passing moments in which there was at least one player in the respective zone. Outside the EPS scheme, with a colour code varying from 0% (red) to 100% (dark green), is indicated the average occupation frequency of all zones (overall fDOF), as well as the averages regarding the defensive (Z1 to Z6) and offensive zones (Z7 to Z12).

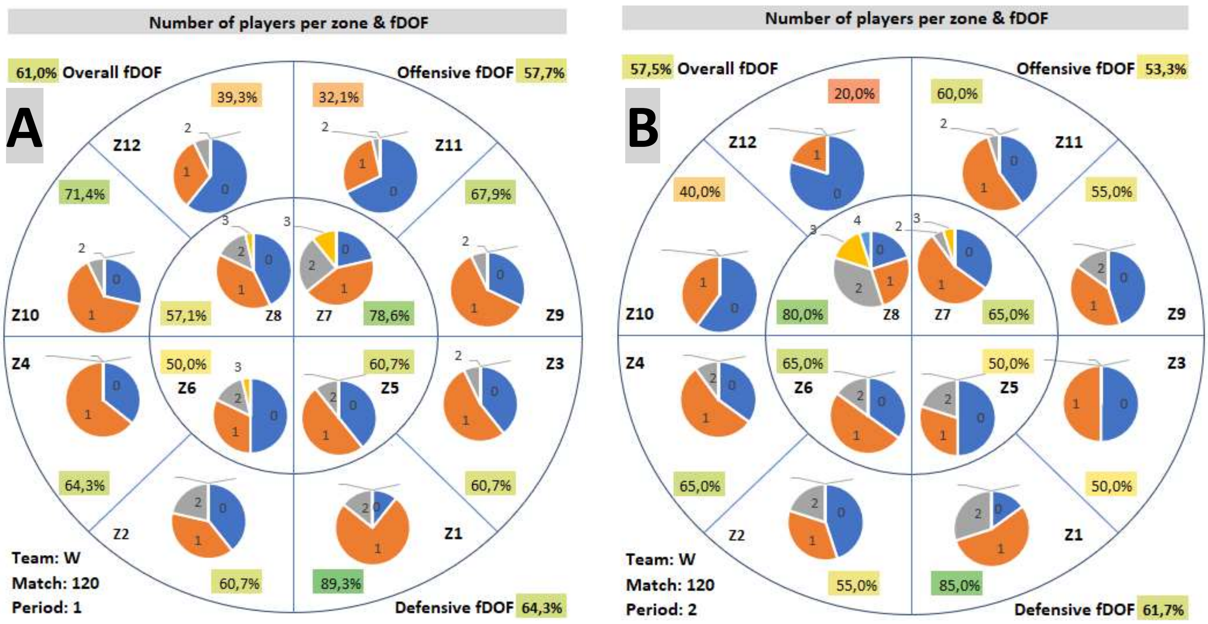



**Figure 5.6:** Exemplar comparison of the occupation frequency in each EPS zone, in two halves of a match (see text for details)

By adding descriptive statistics, trends and patterns in the match can be captured. For the present example, the two halves can be described, by:

- Team (W) global occupation frequency decreased in the second half of the selected match (the overall fDOF decreased from 61% in period 1 to 57.5% in period 2).

- The decrease in the passing possibilities for the ball carrier is linked to the increase, in the second half of redundant players (decreasing the size of the orange slices in the pie charts) in some zones of the EPS (especially in zone 8). This tendency to place more players in the interior zones of the EPS, can partially explain the reduction in the team's occupation frequency in the offensive exterior zones.

- Detailing the EPS interior zones (quadrants), there was a change in the distribution pattern of fDOF, with the areas on the left of the centroid (quadrants Z6 and Z8) showing the increase in the frequency of occupation, while those on the right (quadrants Z5 and Z7) decreased during the second half.

- In the exterior zones, in defensive EPS regions, a tendency to leave unoccupied the central left zone (octant Z2 with 55% of occupation frequency) and the right side (octant Z3 with 50%) was more evident in the second half. These patterns can be seen by the adversary as highlighting exploitable zones in moments of transition.

- In the exterior offensive regions of the EPS, all the zones (octants Z9, Z10 and Z12, with respectively 55%, 40% and 20%), showed a clear decrease in the frequency of occupation in the second half, with exception of the central right zone (octant Z11). The outer spaces of the EPS were not explored so often, which may demonstrate an intention of the W team's players to stay closer to each other, globally implementing a more defensive than offensive behaviour.

As mentioned, outside the EPS schemes in Figure 5.6, it is indicated the average occupation frequency of some groups of zones: a) all 12 zones, i.e., the overall fDOF; b) the 6 more offensive zones; and c) the 6 more defensive zones. Regarding the W team's fDOF values, these averages decline from the $1^{st}$ to the $2^{nd}$ halves of the match, especially in the offensive zones. This might be the result of a tactical tendency to maintain the score advantage that this team (W) had, or eventually due to the growing fatigue levels that can reduce the team's reciprocal compensation. However, some caution is needed in the interpretation of the overall fDOF value. In fact, since the EPS is divided into more zones (12) than the number of ball carrier's outfield players teammates (9), the maximum possible overall fDOF value is 75% and not 100% (without considering the passes made by the goalkeeper). This is because this global value is the average of all zones, and 75% would mean that there would never be more than one player of the ball in possession team in all zones, at all passing instants, in the considered period (i.e., there would never be redundant players in any EPS zone).

## 5.4 Discussion

In this paper, we argue that coaches' qualitative tactical insights can be enhanced with quantitative data if properly translated to their language, using the support of the framework of the ecological dynamics to understand how players interact in the match context to form synergies. In fact, like in other systems, teams are collective unities (Gesbert and Durny, 2017) whose elements (players) interact together to achieve *functional effects that are otherwise unattainable*(Corning, 2018). In high-level football, as in other contexts used to support the "synergism hypothesis" (Corning, 1983), is the functional effects (payoffs) from players' interactions that matter (i.e., team's performance). This reality justifies all the investment in match analysis departments to deeply understand players' interactive cooperation through coaches' tactical lens. Not only from previous matches but also to prepare for future matches, data can be used to communicate how effectively a team was able to perform a function (e.g., keep the ball in possession). In this context, sport science research around functional team synergies can be extremely useful (D. Araújo and K. Davids, 2016). Because synergies exhibit a well-known set of properties (D. Araújo and K. Davids, 2016), the first step to understanding sports teams' behaviour is usually centred on the assessment of the system's dimensional compression. In fact, the definition of a collective variable that captures (compresses) all the independent degrees of freedom (dimensions) of the elements of a team (i.e., their behaviours), in a unique collective variable, is a huge challenge. In the present study, we operationalised the passing possibilities of a team, at any given instant. This method reduced teams' passing affordances to a single number of functional degrees of freedom (fDOF) that can express opportunities for action for the ball carrier and the team. During high-performance matches, football players' interactions occur in the limited space of the effective play space (EPS). By dividing the EPS into twelve zones, it is possible to assess players' distribution on the pitch, quantifying the occupied spaces in a single value, the fDOF. For that, we used the relative position of the Voronoi cells within the EPS, in relation to the centroid of the game. Thus, the number of the team's fDOF is underpinned by the team's instantaneous configuration (i.e., its distribution on the pitch) that represents the global possibilities for the ball carrier to interact with his/her other teammates. Exploring in detail the team's collective configuration at a given point in time, it is possible to capture other synergetic properties. Firstly, the tendencies for interpersonal linkages, i.e., the specific contribution of each player to the collective task of keeping the ball through the pass (D. Araújo and K. Davids, 2016). With this method, we captured in a given instant *who* and *where* the ball carrier is, and to *where* can he passes the ball in the EPS, complementing the information about *who* passes the ball more often to *whom*, as studied through network methods (Ribeiro et al., 2017). In addition to this, by analysing a certain time interval (e.g. half of a match) is possible to capture the tendencies for reciprocal compensation (D. Araújo and K. Davids, 2016). Specifically, how players compensate for the displacements of their teammates to ensure a configuration on the pitch that allows the highest number of fDOF, maintaining the team's collective synergy stable (Scholz and Schöner, 1999).

## 5.5 Conclusion

The proposed method captures the synergies' properties of the team in ball possession, by the quantification of players' global distribution on the pitch. As discussed in the examples presented in Section 5.3, the team's configuration of functional degrees of freedom can be crucial to the emergence of passing opportunities in the game's landscape of affordances. The running examples highlight and stress the applicability for *match analysis* and *training exercises design* purposes, key tasks for high-performance football coaches and other practitioners. The application of the proposed method is not exhausted in the provided examples as they can be used in broader databases and with different time scales and variables (e.g. selecting passes from a certain EPS zone or physical space). Further investigations may consolidate our claim that quantitative data that enables understanding players' interactions (synergies), can support coaches' qualitative interpretation of the game and inherent tactical communication.

### Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| EPS | Effective Play-Space |
| DOF | Degrees Of Freedom |
| fDOF | functional Degrees Of Freedom ... |
| PPA | Point Pattern Analysis |
| VD | Voronoi diagrams |

### Acknowledgement

All data was kindly provided by the STATS© company.

### Disclosure statement

The authors declare no conflict of interest.

### Funding

Duarte Araújo was partly funded by the Fundação para a Ciência e Tecnologia (grant number UIDB/00447/2020, awarded to CIPER-Centro Interdisciplinar para o Estudo da Performance Humana (unit 447). Rui J. Lopes was partly supported by the Fundação para a Ciência e Tecnologia, under Grant Number UIDB/50008/2020 attributed to Instituto de Telecomunicações.

### Data availability

Data was obtained from STATS© company and are available from STATS© with their permission.

## Author contributions

Conceptualisation, N.C., R.J.L. and D.A.; Data curation, N.C., R.J.L and D.F.; Formal analysis, N.C. and R.J.L.; Funding acquisition, D.A.; Investigation, N.C., R.J.L. and D.A.; Methodology, N.C., R.J.L. and D.A.; Software, D.F.; Visualisation, N.C., R.J.L. and D.F.; Supervision, R.J.L. and D.A..; Writing—original draft, N.C.; Writing—review and editing, R.J.L. and D.A. All authors have read and agreed to the published version of the manuscript.

## References


Andrienko, Gennady et al. (2017). *Visual analysis of pressure in football*. Vol. 31. 6, pp. 1793–1839. DOI: 10.1007/s10618-017-0513-2.

Araujo, J et al. (2017). “Ecological cognition : expert decision-making behaviour in sport”. In: *International Review of Sport and Exercise Psychology*.

Araújo, D. and K. Davids (2016). “Team synergies in sport: Theory and measures”. In: *Frontiers in Psychology* 7.SEP, pp. 1–13. DOI: 10.3389/fpsyg.2016.01449Team.

Araújo, D., K. Davids, et al. (2004). “Emergence of sport skills under constraint”. In: *Skill acquisition in sport: Research, theory and practice*. Ed. by A.M. Williams and N.J. Hodges. London: Routledge., pp. 409–433.

Barnabé, Luís et al. (Aug. 2016). “Age-related effects of practice experience on collective behaviours of football players in small-sided games”. In: *Human Movement Science* 48, pp. 74–81. DOI: 10.1016/j.humov.2016.04.007.

Bartlett, Roger et al. (2012). “Analysing team coordination patterns from player movement trajectories in soccer: Methodological considerations”. In: *International Journal of Performance Analysis in Sport* 12.2, pp. 398–424. DOI: 10.1080/24748668.2012.11868607.

Bernstein, N. (1967). *Coordination and Regulation of Movements*. New York: Pergamon Press.

Boots, Barry and Arthur Getis (2020). *Point Pattern Analysis. Web Book of Regional Science. Regional Research Institute, West Virginia University. Edited by Grant Ian Thrall, 1986; Randall Jackson, 2020*.

Brink, Michel S et al. (2018). “What do football coaches want from sport science?” In: *Kinesiology* 50.1, pp. 150–154.

Cakmak, Ali, Ali Uzun, and Emrullah Delibas (2018). “Computational modeling of pass effectiveness in soccer”. In: *Advances in Complex Systems* 21.3-4. DOI: 10.1142/S0219525918500108.

Carrilho, Daniel et al. (Sept. 2020). “Using optical tracking system data to measure team synergic behavior: Synchronization of player-ball-goal angles in a football match”. In: *Sensors (Switzerland)* 20.17, pp. 1–14. DOI: 10.3390/s20174990.

Clemente, Filipe Manuel et al. (2014). “Análise de jogo no Futebol: Métricas de avaliação do comportamento coletivo”. In: *Motricidade* 10.1, pp. 14–26. DOI: 10.6063/motricidade.10(1).1517.

Corning, Peter (1983). *The Synergism Hypothesis: A Theory of Progressive Evolution*. McGraw-Hill, New York.

— (2018). *Synergistic Selection: How Cooperation Has Shaped Evolution And The Rise Of Humankind*. WORLD SCIENTIFIC PUBLISHING CO PTE LTD.

Davids, Keith, Duarte Araújo, and Rick Shuttleworth (2005). “Applications of Dynamical Systems Theory to Football”. In: *Science and Football V: The Proceedings of the Fifth World Congress on Science and Football* i, pp. 537–550.

Di Salvo, Valter et al. (2006). “Validation of Prozone ®: A new video-based performance analysis system”. In: *International Journal of Performance Analysis in Sport* 6.1, pp. 108–119. DOI: 10.1080/24748668.2006.11868359.

Duarte, R and T Frias (2011). “Collective intelligence: An incursion into the tactical performance of football teams”. In: *Proceedings of the First International Conference in Science and Football*, pp. 15–17.

Duarte, Ricardo et al. (2013). “Competing together: Assessing the dynamics of team-team and player-team synchrony in professional association football”. In: *Human Movement Science* 32.4, pp. 555–566. DOI: 10.1016/j.humov.2013.01.011.

Fernandez, Javier and Luke Bornn (2018). “Wide Open Spaces : A statistical technique for measuring space creation in professional soccer”. In: *MIT Sloan Sports Analytics Conference* May, pp. 1–19.

Fonseca, Sofia et al. (2012). “Spatial dynamics of team sports exposed by Voronoi diagrams”. In: *Human Movement Science* 31.6, pp. 1652–1659. DOI: 10.1016/j.humov.2012.04.006.

Frencken, Wouter et al. (2011). “Oscillations of centroid position and surface area of soccer teams in small-sided games”. In: *European Journal of Sport Science* 11.4, pp. 215–223. DOI: 10.1080/17461391.2010.499967.

Frias, T. and R. Duarte (2014). “Man-to-man or zone defense? Measuring team dispersion behaviors in small-sided soccer games”. In: *Trends in Sport Sciences* 21.3, p. 135.

Fullagar, H. H. et al. (2019). “The translation of sport science research to the field: a current opinion and overview on the perceptions of practitioners, researchers and coaches”. In: *Sports Medicine* 49.12, pp. 1817–1824.

Gesbert, Vincent and Annick Durny (Oct. 2017). “A Case Study of Forms of Sharing in a Highly Interdependent Soccer Team During Competitive Interactions”. In: *Journal of Applied Sport Psychology* 29.4, pp. 466–483. DOI: 10.1080/10413200.2017.1287787.

Gibson, J. (1979). *The ecological approach to visual perception*. Boston: Houghton, Mifflin and Company.

Gómez-Jordana, Luis et al. (2019). “Landscapes of passing opportunities in Football – where they are and for how long are available ?” In: *Barça Sports Analytics Summit-2nd edition At: Camp Nou- Barcelona*. November, pp. 1–14.

Gorman, Jamie C. et al. (2017). “Understanding and modeling teams as dynamical systems”. In: *Frontiers in Psychology* 8.JUL, pp. 1–18. DOI: 10.3389/fpsyg.2017.01053.

Gréhaigne, J., P. Godbout, and Z. Zera (2011). “How the “ rapport de forces ” evolves in a soccer match : the dynamics of collective”. In: *Rev. Psicol. Deporte* 20, pp. 747–765.

Gréhaigne, J.F., B. Mahut, and A. Fernandez (2001). “Qualitative observation tools to analyse soccer”. In: *International Journal of Performance Analysis in Sport* 1.1, pp. 52–61. DOI: 10.1080/24748668.2001.11868248.

Gudmundsson, Joachim and Thomas Wolle (2014). “Football analysis using spatio-temporal tools”. In: *Computers, Environment and Urban Systems* 47, pp. 16–27. DOI: 10.1016/j.compenvurbsys.2013.09.004.

Herold, Mat et al. (2019). “Machine learning in men’s professional football: Current applications and future directions for improving attacking play”. In: *International Journal of Sports Science and Coaching* 14.6, pp. 798–817. DOI: 10.1177/1747954119879350.

Jonsson, Gudberg K et al. (2003). “Detection of real-time patterns in sports interactions in football”. In: *L’ethologie applique aujourd’hui* 3, pp. 37–46.

Kim, Jongwon et al. (2019). “The Attacking Process in Football: A Taxonomy for Classifying How Teams Create Goal Scoring Opportunities Using a Case Study of Crystal Palace FC”. In: *Frontiers in Psychology* 10.October, pp. 1–8. DOI: 10.3389/fpsyg.2019.02202.

Kim, S. (2004). “Voronoi Analysis of a Soccer Game”. In: *Nonlinear Analysis: Modelling and Control* 9.3, pp. 233–240.

Li, Zong-Ming (2006). “Functional Degrees of Freedom”. In: *Motor Control* 10, pp. 301–310.

McLean, Scott et al. (2018). “The effect of playing formation on the passing network characteristics of a professional football team”. In: *Human Movement* 2018.5, pp. 14–22. DOI: 10.5114/hm.2018.79416.

Merlin, Murilo et al. (2020). “Exploring the determinants of success in different clusters of ball possession sequences in soccer”. In: *Research in Sports Medicine* 28.3, pp. 339–350. DOI: 10.1080/15438627.2020.1716228.

Moura, Felipe Arruda et al. (2012). “Quantitative analysis of Brazilian football players’ organisation on the pitch”. In: *Sports Biomechanics* 11.1, pp. 85–96. DOI: 10.1080/14763141.2011.637123.

Narizuka, Takuma, Yoshihiro Yamazaki, and Kenta Takizawa (2021). “Space evaluation in football games via field weighting based on tracking data”. In: *Scientific Reports* 11.1, pp. 1–8. arXiv: 2001.11629.

Occhino, J., C. Mallett, and S. Rynne (2013). “Dynamic social networks in high performance football coaching”. In: *Physical Education and Sport Pedagogy* 18.1, pp. 90–102.

Okihara, K. et al. (2004). “Compactness as a strategy in a soccer match in relation to a change in offence and defense”. In: *J Sports Science* 22.6, p. 515.

Passos, Pedro, Duarte Araújo, and Keith Davids (2013). “Self-organization processes in field-invasion team sports implications for leadership”. In: *Sports Medicine* 43.1, pp. 1–7. DOI: 10.1007/s40279-012-0001-1.

Pennestri, E., M. Cavacece, and L. Vita (2005). “On the Computation of Degrees-of-Freedom: A Didactic Perspective”. In: *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. January, pp. 1733–1741. DOI: 10.1115/DETC2005-84109.

Perl, Jürgen and Daniel Memmert (2016). “Soccer analyses by means of artificial neural networks, automatic pass recognition and voronoi-cells: An approach of measuring tactical success”. In: *Advances in Intelligent Systems and Computing*. Vol. 392. Springer Verlag, pp. 77–84. DOI: 10.1007/978-3-319-24560-7_10.

Pina, Tiago J., Ana Paulo, and Duarte Araújo (July 2017). “Network characteristics of successful performance in association football. A study on the UEFA champions league”. In: *Frontiers in Psychology* 8.JUL. DOI: 10.3389/fpsyg.2017.01173.

Reade, Ian, Wendy Rodgers, and Katie Spriggs (2008). “New Ideas for High Performance Coaches: A Case Study of Knowledge Transfer in Sport Science”. In: *International Journal of Sports Science & Coaching* 3.3, pp. 335–354. DOI: 10.1260/174795408786238533.

Rein, Robert and Daniel Memmert (2016). “Big data and tactical analysis in elite soccer: future challenges and opportunities for sports science”. In: *SpringerPlus* 5.1. DOI: 10.1186/s40064-016-3108-2.

Rein, Robert, Dominik Raabe, and Daniel Memmert (Oct. 2017). ““Which pass is better?” Novel approaches to assess passing effectiveness in elite soccer”. In: *Human Movement Science* 55, pp. 172–181. DOI: 10.1016/j.humov.2017.07.010.

Ribeiro, João et al. (Sept. 2017). “Team Sports Performance Analysed Through the Lens of Social Network Theory: Implications for Research and Practice”. In: *Sports Medicine* 47.9, pp. 1689–1696. DOI: 10.1007/s40279-017-0695-1.

Ric, Angel et al. (Oct. 2016). “Soft-assembled multilevel dynamics of tactical behaviors in soccer”. In: *Frontiers in Psychology* 7.OCT. DOI: 10.3389/fpsyg.2016.01513.

Riley, Michael et al. (2011). “Interpersonal synergies”. In: *Frontiers in Psychology* 2.MAR. DOI: 10.3389/fpsyg.2011.00038.

Robertson, R. (1995). “Glocalization: Time-space and homogeneity-heterogeneity”. In: *Global modernities* 2.1, pp. 25–44.

Rosén, Emil (2015). “Analysis and visualization of collective motion in football : Analysis of youth football using GPS and visualization of professional football”. PhD thesis. Uppsala Universitet.

Scholz, John P. and Gregor Schöner (1999). “The uncontrolled manifold concept: Identifying control variables for a functional task”. In: *Experimental Brain Research* 126.3, pp. 289–306. DOI: 10.1007/s002210050738.

Shahal, Shir et al. (2020). “Synchronization of complex human networks”. In: *Nature Communications* 11.1, pp. 1–10. DOI: 10.1038/s41467-020-17540-7. arXiv: 1906.03262.

Silva, Pedro, Ricardo Duarte, et al. (2014). “Field dimension and skill level constrain team tactical behaviours in small-sided and conditioned games in football.” In: *Journal of sports sciences* November, pp. 1–9. DOI: 10.1080/02640414.2014.961950.

Silva, Pedro, Júlio Garganta, et al. (2013). “Shared knowledge or shared affordances? insights from an ecological dynamics approach to team coordination in sports”. In: *Sports Medicine* 43.9, pp. 765–772. DOI: 10.1007/s40279-013-0070-9.

Silva, Pedro, Luís Vilar, et al. (2016). “Sports teams as complex adaptive systems: manipulating player numbers shapes behaviours during football small sided games”. In: *Springerplus* 5.Heim 1958, p. 191. DOI: 10.1186/s40064.

Stefan, K, Walter Kob, and Rolf Schilling (1997). “Dynamics of the rotational degrees of freedom in a supercooled liquid of diatomic molecules”. In: *Phys. Rev. E, 56(cond-mat/9704166), 5450.* arXiv: 9704166v1 [arXiv:cond-mat].

Tenga, A., A. Mortensholm, and P. O’Donoghue (Sept. 2017). “Opposition interaction in creating penetration during match play in elite soccer: evidence from UEFA champions league matches”. In: *International Journal of Performance Analysis in Sport* 17.5, pp. 802–812. DOI: 10.1080/24748668.2017.1399326.

Travassos, Bruno et al. (2012). “Practice task design in team sports: Representativeness enhanced by increasing opportunities for action”. In: *Journal of Sports Sciences* 30.13, pp. 1447–1454. DOI: 10.1080/02640414.2012.712716.

Vilar, Luís et al. (2013). "Science of winning soccer: Emergent pattern-forming dynamics in association football". In: *Journal of Systems Science and Complexity* 26.1, pp. 73–84. DOI: 10.1007/s11424-013-2286-z.

Wade, A. (1998). *Principles of team play*. Reedswain Inc..

# Chapter 6

# From optical tracking to tactical performance via Voronoi diagrams: team formation and players' roles constrain interpersonal linkages in high-level football

Caldeira, N., Lopes, R.J., Fernandes, D. & Araújo, D. (2022, Sensors, 23(1), 273)

## Abstract

Football performance behaviour relies on the individual and collective perceptual attunement to the opportunities for action (affordances) available in a given competitive environment. Such perception–action coupling is constrained by players' spatial dominance. Aiming to understand the influence of team formation and players' roles in their dynamic interaction (interpersonal linkages), Voronoi diagrams were used to assess the differences in players' spatial dominance resulting from their interactions according to ball-possession status in high-performance football.

Notational (i.e., team formation, players' role, and ball-possession status) and positional data (from optical sensors) from ten matches of the men's French main football league were analysed. Voronoi diagrams were computed from players' positional data for both teams. Probability density functions of the players' Voronoi cell areas were then computed and compared, using the Kolmogorov–Smirnov test, for the different variables (i.e., team formation, player role, and ball-possession status) and their classes. For these variables, the players' Voronoi cell areas presented statistical differences, which were sensitive to team formation classes (i.e., defenders, midfielders, and forwards) and relative pitch location (interior or exterior in the effective playing space). Differences were also found between players with similar roles when in different team formations.

Our results showed that team formation and players' roles constrain their interpersonal linkages, resulting in different spatial dominance patterns. Using positional data captured by optical sensors, Voronoi diagrams can be computed into compound variables, which are meaningful for understanding the match and thus offer information to the design representative training tasks.

## Keywords

Affordances, Spatial dominance patterns, Performance, Team synergies, Voronoi cells

## 6.1 Introduction

In recent years, the technological progress around spatial location systems and positional data has had a growing impact on our societies and in all investigation fields (Long and Nelson, 2013; Miller et al., 2019), including sport sciences (Rico-González et al., 2020) and high-performance football (Memmert, Lemmink, and Sampaio, 2017).

This increase in the volume of data (Memmert and Rein, 2018) can better inform coaches about the performance of their teams, including tactical behaviour (Hewitt, Greenham, and Norton, 2016). Importantly, teams' performance is based on the coordinated decisions of their players (D. Araújo, P. Silva, and Ramos, 2014), which form team synergies (spatial-temporal patterns of coordination) guided by shared affordances (D. Araújo and K. Davids, 2016).

Affordances are properties of the environment that relate to the individual characteristics, implemented by specific perception–action cycles, i.e., "action specific relations that exist between the skills/capacities of an individual performer and the action relevant properties of a [perceived environmental] task" (D. Araújo and K. Davids, 2016)[p4]. Training develops football players to become attuned to affordances of the match, namely those constrained by match phases such as ball possession status(Fonseca et al., 2012; Pedro Silva, Vilar, et al., 2016). Such *attunement* is better developed if coaches pursue the *representativeness* of their training exercises (Pinder et al., 2011) through the manipulations of relevant task constraints (Renshaw and J. Y. Chow, 2019).

When training for a match, coaches constrain the emergence of the affordances perceived by players and, consequently, their interactions with teammates and opponents (Ric et al., 2017). For this purpose, there are evidence-based match-space criteria for training design. For example, coaches can define the space of their training exercises from generic benchmarks such as the *Game Intensity Index* (GII) (J. Chow et al., 2013). The GII establishes a parallelism of the training surface in terms of square meters per player with that of competition. However, this is a very broad reference, which in high-competition football is equivalent to an area of $325m2$ per player $(68mx105m/22players)$. It is no surprise that studies with *small-sided and conditioned games* (SSCG) suggest the use of *relative space per player* (RSP). The RSP corresponds to an area per player that derives from the smallest rectangle where all field players fit (Fradua et al., 2013). Similarly, Silva and colleagues (2015) divided the *effective play space* (EPS), which is the polygon of the smallest convex hull, by the number of players. Both RSP proposals have the merit of measuring what occurs in game spaces in training and competition. However, they do not consider the space outside the EPS and, consequently, the impact of team formation on players' and teams' metrics.

During a football game, players do not move randomly throughout the space (Pedro Silva, Travassos, et al., 2014). Players' movements and team coordination (Carrilho et al., 2020) are constrained by strategy (D. Araújo, P. Silva, and Ramos, 2014), including the game system or *team formation* (McLean et al., 2018). These formations constrain the spatial organization of players in a team (Müller-Budack et al., 2019) and thus how they can form synergies (Carrilho et al., 2020). Team formations are especially relevant to understand *interpersonal linkages* as "the specific contribution of each element to a group task" (D. Araújo and K. Davids, 2016)[p8]. Team formations are typically represented via a set of 3 or 4 numbers that indicate the number of players in each line (or sector) and express how the team is organized on the pitch. For example, "3-5-2" expresses that the team formation is composed of three defenders, five midfielders, and two attackers (Müller-Budack et al., 2019). Moreover, each player in his/her sector has a specific spatial *role* (Riezebos, 2021; Memmert, Raabe, et al., 2019) or playing position (Riezebos, 2021), which is tagged with a specific designation. Usually, it describes the player's main role, considering both the sector to which they belong (e.g., defenders—all outfield players that are more implicated in defensive tasks) and information about their corridor and side (e.g., right lateral defender or left centre midfielder). Currently, in high-performance football, 3-5-2, 3-4-1-2, and 4-2-3-1 are among the most commonly used tactical team formations (Hewitt, Greenham, and Norton, 2016; Merlin et al., 2020).

Team formation affects performance by, for example, influencing key performance indicators (KPIs) such as the *Effective Playing Space* or *Team Separateness* (Memmert, Raabe, et al., 2019). Although the clear influence of team formations and players' role in individual and team performance, its relevance for understanding the synergies that emerge from players interaction in competition are still unclear.

Aiming to bridge this gap, we argue that if the players' roles within a team formation influence team synergies, then it will be possible to identify their specific contributions. Nowadays, we can compute positional data obtained by different types of sensors (e.g., optical tracking, GPS, or RFID) and calculate team spatial–temporal patterns such as *spatial heatmaps* (Fernández, Bornn, and Cervone, 2019), *major ranges* (Yue et al., 2008), or *Voronoi diagrams* (VD). VD in particular assess players' *space dominance* (Efthimiou, 2021), as well as, at the team synergetic level, their interpersonal linkages (D. Araújo and K. Davids, 2016)[p8], (e.g., maintain ball possession).

This paper aims to understand the influence of team formation and players' roles in the players' spatial dominance resulting from the dynamic interaction (interpersonal linkages) of both teams. Therefore, we expect the following:

- Interpersonal linkages among players are expressed by their spatial interactions and are constrained by team formation and players' roles.
- Players' spatial dominance could be operationalized by Voronoi diagrams (and related spatial statistics), which could capture differences according to team formations, players' roles, and ball-possession status.

## 6.2 Materials and Methods

### 6.2.1 Data sources

The data used in this paper were provided by STATS© and obtained through their systems of semi-automatic tracking (Di Salvo et al., 2006) in ten *Ligue 1* matches (France) of the 2019-2020 season. Data were composed of players' positional data (longitudinal and lateral coordinates) sampled at 10Hz, and notational data describing match events (representing players' contacts with the ball) and possession episode (PE) information (initial and final instants, team with ball possession).

### 6.2.2 Data processing

The raw data were processed before analysis using the following procedures:

- For each match, the determination of team formations was performed in two steps:
  1. Using the STATS Edge Analysis application:
     a. The match time was divided into six periods of 15 minutes, as suggested by Duarte and colleagues (2013); each period was subdivided in case there was a substitution.
     b. The average longitudinal and lateral position of each player was computed throughout each time period.
  2. From these results and following the suggestion of Carling (Carling and Dupont, 2011) and Bradley and colleagues (2011), a panel of experts identified both team formations during each of the match intervals. The panel was composed of five coaches with at least ten years of professional experience at the highest level and holding an UEFA PRO certification.
- Team formation, players' roles, and ball-possession status were considered crucial to data analysis in this paper; consequently, matches and periods within the matches were grouped and selected according to the following criteria:
  a. For each match, there was an analysed team and an opponent team. For all matches and time periods, the opponent team was always the same and organized under the same team formation (3-5-2). The analysed team was always a different one, forming two groups of five matches. In one group, the analysed team played mostly in a 4-2-3-1 team formation, and in the other group mostly with a 3-4-1-2 team formations.
  b. Within each match, only periods in which teams maintained their team formation (4-2-3-1 or 3-4-1-2 for the analysed team and 3-5-2 for the opponent team) were used. All other periods, either where teams played with different formations or where they were not complete (e.g., after a red card), were discarded.
- Match periods were further filtered so that only open plays were considered; i.e., set plays and time gaps without play were discarded. Each open play was subdivided into ball-possession episodes (PEs). Each PE starts at the instant when a team recovers the ball and ends when that team loses control of the ball. According to STATS© reference manual (STATS, 2019), at least two consecutive events were necessary to form a PE. Each PE was classified, given the analysed team's ball possession status, as *in possession* or *out of possession*. The 4-2-3-1 formation comprised 999

possession episodes (499 in possession, 500 out of possession), whilst the 4-2-3-1 formation comprised 1199 possession episodes (601 in possession, 598 out of possession).

- · The role of each player of the analysed team was classified according to his spatial average position in the respective team formation. Table 6.1, adapted from Riezebos (Riezebos, 2021), identifies these roles for the two team formations: 4-2-3-1 and 3-4-1-2.

| **4-2-3-1** | | **3-4-1-2** | |
|---|---|---|---|
| *Tag* | *Description* | *Tag* | *Description* |
| GK | Goalkeeper | GK | Goalkeeper |
| LLB | Left Lateral Back | CCB | Centre Central Back |
| LCB | Left Central Back | LCB | Left Central Back |
| RCB | Right Central Back | RCB | Right Central Back |
| RLB | Right Lateral Back | LLM | Left Lateral Midfielder |
| LCM | Left Centre Midfielder | LCM | Left Centre Midfielder |
| RCM | Right Centre Midfielder | RCM | Right Centre Midfielder |
| LAM | Left Attacking Midfielder | RLM | Right Lateral Midfielder |
| CAM | Centre Attacking Midfielder | CAM | Centre Attacking Midfielder |
| RAM | Right Attacking Midfielder | LCF | Left Centre Forward |
| CF | Centre Forward | RCF | Right Centre Forward |

**Table 6.1:** Player's role in 4-2-3-1 and 3-4-1-2 team formations.

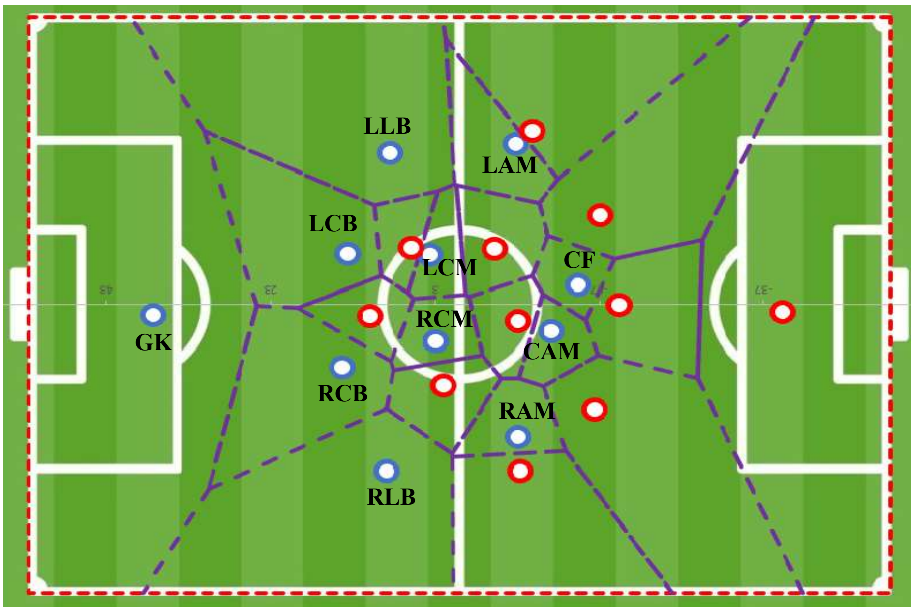
- The average value of the Voronoi cell area (VA) during the PE was computed for each player of the analysed team. VAs are computed at each time frame, using the procedures described by Kim (Kim, 2004), considering all the players of both teams.

Figure 6.1 illustrates the Voronoi diagrams (VDs) obtained from players' roles with different analysed team formations. Although VDs are computed at each time frame, in Figure 6.1, each player is represented at the average position along the longitudinal and lateral axes for the five matches considered, and their Voronoi area is circumscribed by dashed lines. Players from the analysed teams (in blue) are indicated using their role tag.

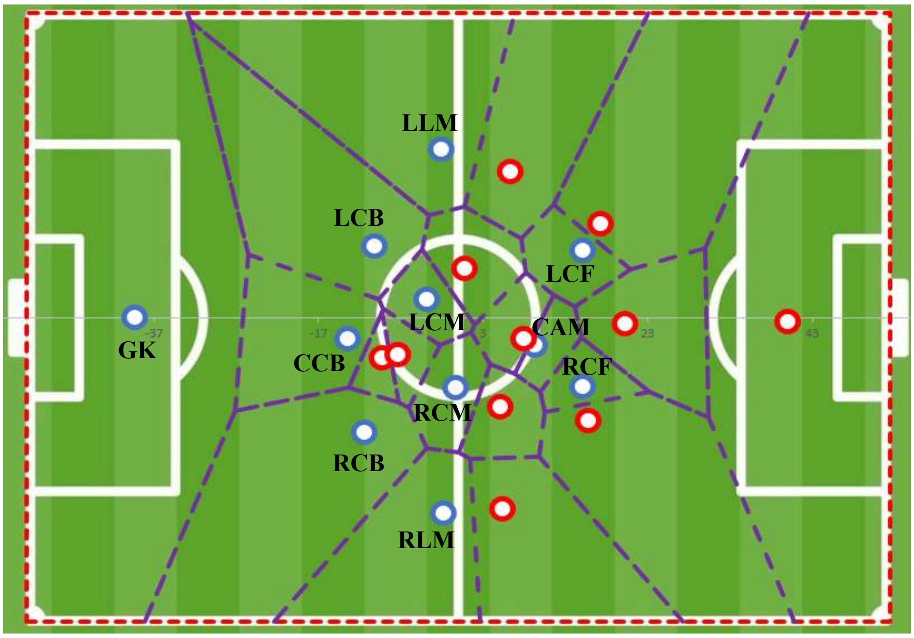
The VDs in Figure 6.1 exemplify the influence of the opponent team in the VA of the analysed team players, thus capturing the interaction of all players on the pitch and not only with his teammates (Santana, 2011). This interaction is crucial for the relative position of a given player in the effective play space (EPS). For example, the RCF and LCF in the 3-4-1-2, formation, despite being the most forward elements of their team, occupy interior areas in the game space due to the interaction with their opponents.

### 6.2.3 Statistical analysis methods

Statistical analysis was performed by computing and comparing the probability density functions of the players' mean Voronoi areas (VAs) during each possession episode (PE). Probability density functions are represented as violin plots using kernel smoothing and compared using the Kolmogorov–Smirnov statistic. For the Kolmogorov–Smirnov test, "H0: same distribution" is used as the null hypothesis, with a significance level set at .05 (i.e., the alternative hypothesis is assumed if $p < .05$).




**(a)** 4-2-3-1 Team Formation




**(b)** 3-4-1-2 Team Formation

**Figure 6.1:** Voronoi diagrams for analysed teams (blue) in two team formations (a. 4-2-3-1 and b. 3-4-1-2) and the opposing team (red)

## 6.3 Results

To compare the Voronoi areas (VAs) of players' roles, the results for the analyzed teams were organized into two sections:

a. Section 6.3.1 provides the players' Voronoi area (VA) probability density functions violin plots for both team formations. The probability density function of each player is compared according to ball possession status and according to their role within the same team formation.

b. Section 6.3.2 compares the probability density functions of players according to their role and between the two different team formations.

The numerical values for all the results presented are provided as Supplementary Materials.

### 6.3.1 Comparing players' VA within the same team formation

The results of comparing players' VA, according to their role and ball possession status (in possession and out of possession) within the 4-2-3-1 team formation, are presented in the violin plots (a) and heatmaps (b and c) of Figure 6.2. The values in Figures 6.2 correspond to the Kolmogorov–Smirnov statistic values quantifying the differences between VAs and their statistical significance.

In Figure 6.2, the value indicated for each role $i$ was computed as $V_{KS}(i) = -log(KS(P_i, Q_i))$ where $KS$ is the Kolmogorov-Smirnov statistic and $P_i$,$Q_i$ are the VA probability density functions for a player with role $i$ when the analysed team is *in* and *out* of ball possession, respectively. Differences between ball possession status were statistically significant ($p < .05$) except for roles highlighted in bold.

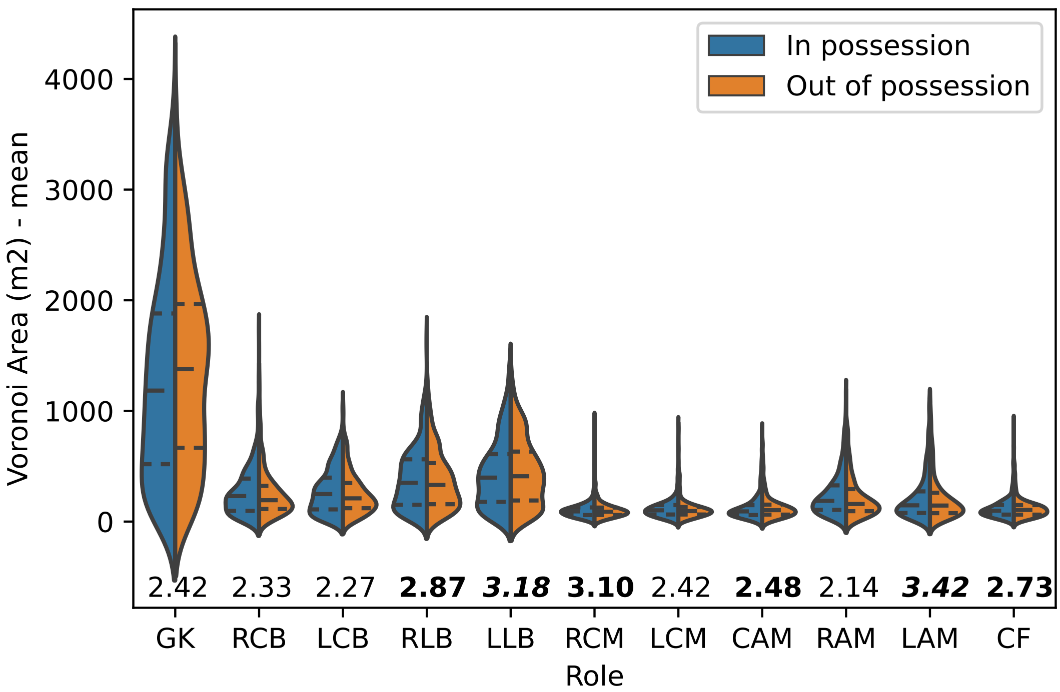
The differences between VAs for all possible role pairs are represented in the heatmaps of Figure 6.2. The value indicated in cell $i,j$ was computed as $V_{KS}(i,j) = -log(KS(P_i, Q_j))$ where KS is the Kolmogorov-Smirnov statistic and $P_i$, $Q_j$ are, respectively, the VA probability density functions of players with role $i$ and $j$. Differences between role pairs were statistically significant ($p < .05$) except for pairs highlighted in bold.

Figure 6.2 clearly expose the differences in the distribution of players' VA, according to their role and ball possession. Apart from the GK's specific case, the violin plots also differentiate players' roles according to their sector (back vs. forward) and to their relative location (interior vs. exterior) in the *Effective Play Space* (EPS). Despite the general trend to find significant differences in the VA of players with different roles, ball-possession status also has an impact on VA similarity, mainly in the cases where differences were non-significant.

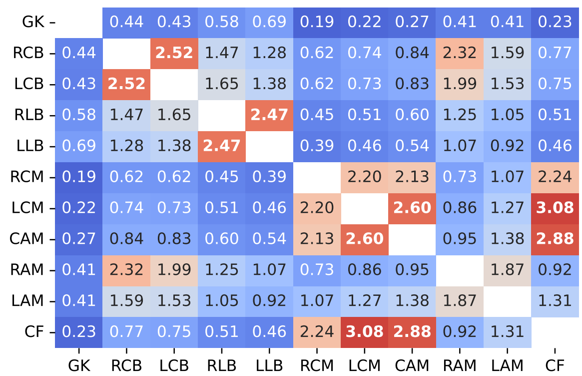
When the analysed teams were in possession of the ball, the non-significant differences were observed between players of the same sector, namely, between central backs (RCB and LCB), lateral defenders (RLB and LLB), and midfielders (CAM and LCM), and also between the CF and two midfield interior players (CAM and LCM). On the other hand, when the analysed teams were out of ball possession, non-significant differences remained between RCB and LCB and between CAM and CF. Except for the new non-significant differences between the defensive midfielders (RCM and LCM) and between wingers (RAM and LAM), all the others were now statistically significant.

The same process was applied to the 3-4-1-2 team formation. Players' VA distribution is presented in the violin plots and their Kolmogorov-Smirnov statistics heatmaps in Figure 6.3.

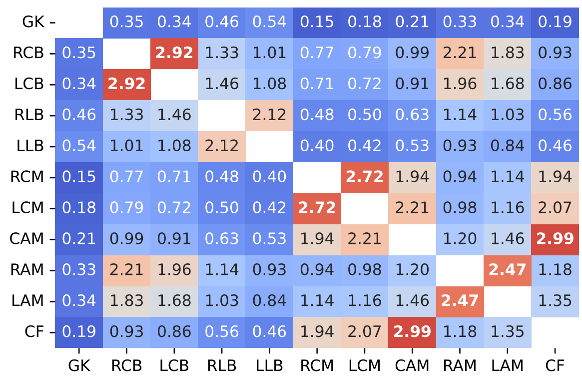
Similarly, to the 4-2-3-1 team formation, smaller VAs were found for players who usually play in the interior regions of the EPS (RCM, LCM, CAM, RCF, and LCF). In addition, the third central back (CCB) seems to have even smaller areas than the players of the first defensive line (RCB and LCB).




**(a)** Violin plots (in/out of possession).




**(b)** KS heatmap (in possession).




**(c)** KS heatmap (out of possession).

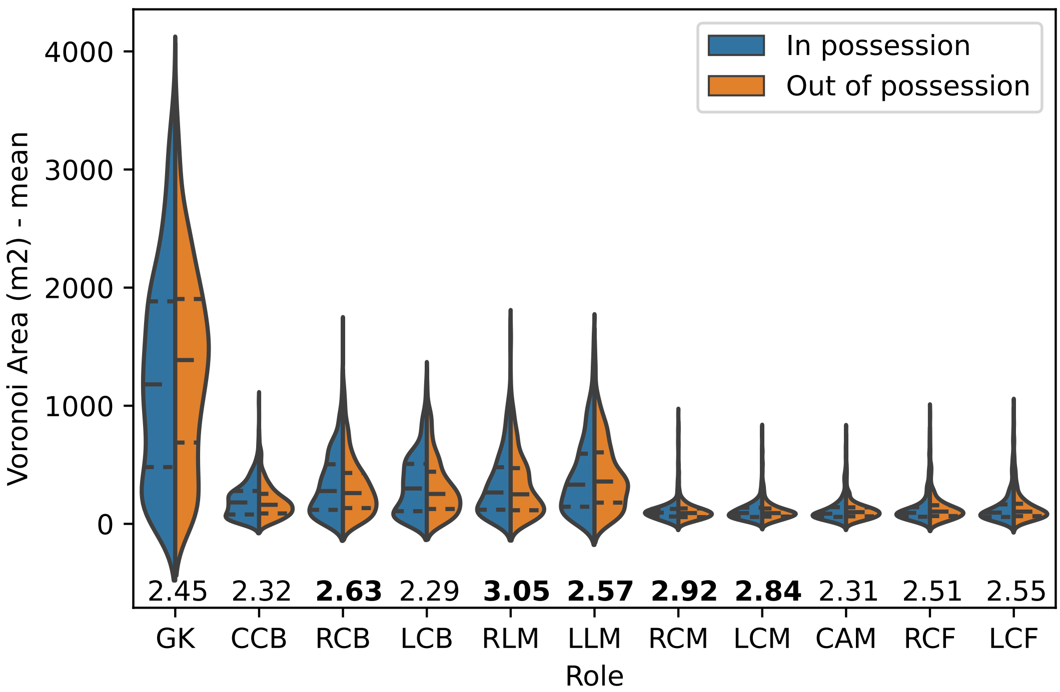
**Figure 6.2:** Players' Voronoi area probability density function in the 4-2-3-1 team formation.
*Note:* Violin plots (a) and heatmaps (b and c) comparing players' Voronoi area probability density function (less similar in blue, more similar in red). The differences that are statistically not relevant are highlighted in **bold**)

.

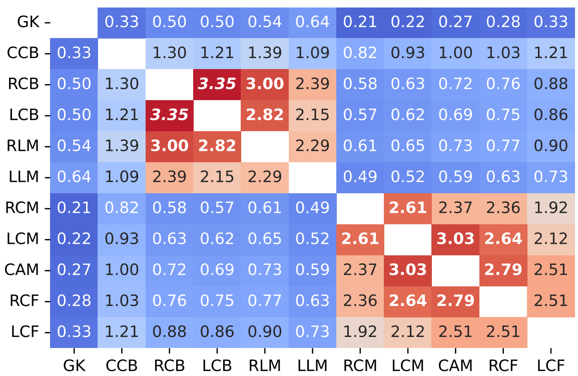
Once more, the ball-possession status significantly influenced only some of the roles (GK, CCB, LCB, CAM, RCF, and LCF). All the other roles presented non-significant differences (highlighted in bold).

In this team formation, VA distribution continues to generally allow the differentiation between players' roles. However, the number of non-significant differences increases, showing a higher similarity between the VA of different roles, e.g., in the defensive line (CCB being the exception). The VA differences between role pairs were statistically significant ($p < .05$), with the following exceptions (highlighted in bold in Figure 6.3):

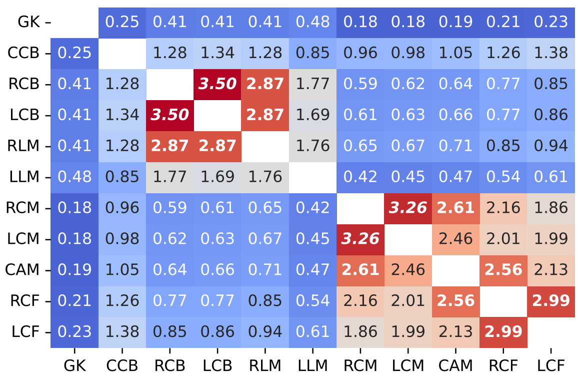
1. in possession: RCB – LCB; RCB – RLM; LCB – RLM; RCM –LCM; LCM – CAM; LCM – RCF; CAM




**(a)** Violin plots (in/out of possession).




**(b)** KS heatmap (in possession).




**(c)** KS heatmap (out of possession).

**Figure 6.3:** Players' Voronoi area probability density function in 3-4-1-2 team formation.
*Note:* Violin plots (a) and heatmaps (b and c) comparing players' Voronoi area probability density function (less similar in blue, more similar in red). The differences that are statistically not relevant are highlighted in **bold**)

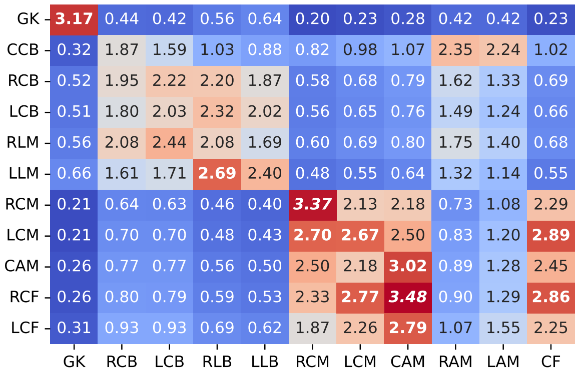
.

– RCF;

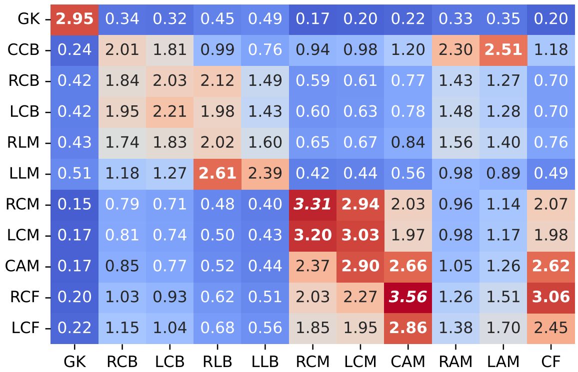
2. out of possession: RCB – LCB; RCB – RLM; LCB – RLM; RCM – LCM; RCM – CAM; RCF – CAM; RCF – LCF.

### 6.3.2 Comparing players' VA between different team formations

Finally, the distribution of VA was compared according to players' roles between team formations (Figure 6.4).




**(a)** KS heatmap (in possession).




**(b)** KS heatmap (out of possession).

**Figure 6.4:** Comparison of the VA of players' roles in both team formations

Both comparisons reveal a natural similarity between players in the same sector. However, the degree of similarity is not equal across sectors and shows important differences between defenders, midfielders, and attackers. In fact, in the defensive sector, all central backs showed significant differences between the TFs. In the lateral backs, the only non-significant difference was found between the LB and the RM. In the lateral backs, the only non-significant difference was found between the LB and the RM.
Concerning the midfielders, distinct analyses should be made for the interior and exterior players. In fact, several non-significant differences were found between the two TFs regarding the interior roles, showing that for this sub-group, the choice between the 4-2-3-1 and 3-4-1-2 formation did not have a big influence on players' VA, regardless of the team's ball-possession status.

However, for the wingers (RAM and LAM) of the 4-2-3-1 formation, a clear different spatial pattern was found in these players' VA distribution, which does not resemble any other role in the 3-4-1-2 TF (with the exception of the CCB).
Finally, for the attackers, several non-significant differences were found in the comparisons of the central forwards' VA. These are found between players of the attacking sector from the two TFs and between players of the attacking and midfield sectors. This was especially evident in the comparisons with the attacking midfielders (CAM).

## 6.4 Discussion

The aim of this study was to understand the influence of team formation and players' roles in their dynamic interaction (interpersonal linkages). For this purpose, Voronoi diagrams were used to assess the differences in players' spatial dominance resulting from their interactions according to ball-possession status in high-performance football teams.

The observed results support some important reflections on the division of space, according to their team formations (TF), their roles (especially the sector and EPS interior/exterior positioning), and the ball possession status. When analyzing the spatial patterns within the same TF, the differences between players' VA were generally found to be statistically significant according to their roles.

The results from Fonseca and colleagues (2012), showing the influence of ball possession status on Voronoi cell area (VA), do not universally apply but are dependent on players' roles. With few some exceptions, these differences demonstrate the existence of different affordances according to players' roles, especially between sectors and according to the relative location (interior or exterior) of each player in the effective play space (EPS). The VA of each player role varies according to these two general criteria, influencing players' interpersonal linkages in the establishment of collective synergies.

Resulting from the teams' interactions and due to the nature of the VA metric, players who usually act in the interior of the EPS (midfielders and centre forwards) had smaller areas; players who play in the periphery of the EPS had larger VAs; and the VAs of the wingers or attacking midfielders (RAM and LAM) were intermediate (possibly because they alternate between interior and exterior spaces in the EPS). Additionally, more defensive players (who occupy positions closer to their own goal) generally deal with wider VAs, while the most offensive players usually deal with smaller VAs.

Although some role pairs show a certain degree of symmetry (RCB – LCB or RCM – LCM), this is not found globally. This is the case for the attacking midfielders (AMR – AML) in the 4-2-3-1 TF or the players of the lateral corridors (RM – LM) in the 3-4-1-2 TF. In comparing the two TFs analysed, it is important to note how VA patterns significantly change across the players of the defensive sector, exposing differences in the spatial affordances when a team plays with a first defensive line with three or four players. However, other roles were very similar in both team formations. Apart from the expected case of the GK, this similarity was especially true in the interior (centre) midfield positions. Our results also underpin some practical clues that we find relevant to the football coaches' work. First is the need to consider TF and players' roles as important constraints during the design of training exercises (McLean et al., 2018). This implies the need to manipulate and measure the space per player role that actually occurs within these drills in reference to the competitive patterns (Carrilho et al., 2020).

Additionally, the fact that no significant differences were found between some players' roles (e.g., between the two central backs or the two more defensive midfielders—a fact found in both TFs and independent of ball possession status) may indicate that players can eventually switch more easily between these roles. This is particularly relevant in situations out of the game plan, e.g., when replacing an injured player.

However, as most role-pair comparisons presented significant differences, coaches need to be aware of the difficulty for players to adapt to the spatial affordances associated with different roles. Even within the same sector, switching sides may imply different spatial affordances due to the non-symmetry detected in some roles. The difference between players' role patterns that were expected to be similar between the two TFs highlights the need for coaches to dedicate enough training time to attune players, individually and collectively, to the spatial affordances that emerge from the strategical option for a given TF (Tallapragada and Sudarsanam, 2017). Coaches should be aware that a sudden change in TF may cause more difficulties in adapting to their players than to their opponents. Moreover, differences in VA spatial patterns, according to the TF and players' roles, may also imply the need to properly consider them in the long-term training processes of youth footballers. For example, by introducing a certain degree of variability in the role, coaches can avoid a possible early specialisation (Araujo et al., 2009).

Voronoi diagrams can thus be considered a useful tool to study teams in competitions (match analysis) and as an auxiliary metric to the design of representative training exercises. After characterizing the VA of each player role in a given team organization (TF) during competition, the next step is to use the same tools in training exercises. By measuring players' VA in each exercise, it will be possible to compare the data obtained in the context of training with the values of the respective team in the context of competition. This can constitute a possible way to quantify, in spatio-temporal terms, their representativeness degree, with more detail than with *Game Intensity Index* (J. Chow et al., 2013) or the *Relative space per player* (Fradua et al., 2013) (Pedro Silva, Esteves, et al., 2015). In particular, and contrary to the relatively simplistic idea proposed in (Olthof, Frencken, and Lemmink, 2018) that 320 m2 per player would be more representative to design Small-Sided and Conditioned Games (SSCG), VD can help coaches to more effectively manipulate training surfaces. In fact, the adoption of VD to assess players' spatial patterns can help in the definition of more suitable dimensions for each training exercise, adjusting them to the global TFs and players' roles. The use of VD-based tools can contribute to achieving a higher degree of representativeness of training exercises, in both SSCG and large-sided games (Gonçalves et al., 2017).

The differences between the spatial patterns of players' roles within the same TF also underline the importance of coaches designing *supraspecific* training tasks, i.e., the specific training that goes beyond simply training with the ball (Tamarit, 2013). *Supraspecificity* implies the design of tasks that are based not only on the football's general dynamics but also on the specific constraints of each team (e.g., coach's game model, including team formations), which has an important role in the development of the interpersonal linkages and collective synergies that underpin team performance (D. Araújo and K. Davids, 2016).

## 6.5 Conclusion

This study exposes how TF and players' roles influence their VA spatial patterns. It underlines the importance of considering these features when coaches design training exercises, as they constrain players' interpersonal linkages in the establishment of team synergies and collective performance. Consequently, this study reinforces the need to train ecologically (Keith Davids, Duarte Araújo, and Shuttleworth, 2005), as a pathway for players' progressive attunement to the affordances of the competitive environment, i.e., through representative training (Pinder et al., 2011). We believe that the assessed methods and their results can contribute to leveraging the utility of optical tracking systems in sports and ultimately to the tactical performance of high-level football teams.

## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| CLA | Constraints-Led Approach |
| EPS | Effective Play Space |
| GII | Game Intensity Index |
| KS | Kolmogrov-Smirnov |
| PE | Possession Episodes |
| RSP | Relative Space per Player |
| SSCG | Small-Sided and Conditioned Games |
| TF | Team Formation |
| VA | Voronoi Area |
| VD | Voronoi Diagrams |
| *Note:* | Players' role in 4-2-3-1 and 3-4-1-2 team formations are defined in Table 6.1. |


## Acknowledgement

All data was kindly provided by the STATS© company.


## Disclosure statement

The authors declare no conflict of interest.


## Funding

Duarte Araújo was partly funded by the Fundação para a Ciência e Tecnologia (grant number UIDB/00447/2020, awarded to CIPER-Centro Interdisciplinar para o Estudo da Performance Humana (unit 447). Rui J. Lopes was partly supported by the Fundação para a Ciência e Tecnologia, under Grant Number UIDB/50008/2020 attributed to Instituto de Telecomunicações.


## Data availability

Data was obtained from STATS© company and are available from STATS© with their permission.

## Author contributions

Conceptualisation, N.C., R.J.L. and D.A.; Data curation, N.C., R.J.L and D.F.; Formal analysis, N.C. and R.J.L.; Funding acquisition, D.A.; Investigation, N.C., R.J.L. and D.A.; Methodology, N.C., R.J.L. and D.A.; Software, D.F.; Visualisation, N.C., R.J.L. and D.F.; Supervision, R.J.L. and D.A..; Writing—original draft, N.C.; Writing—review and editing, R.J.L. and D.A. All authors have read and agreed to the published version of the manuscript.

## References


Araujo, Duarte et al. (2009). “The development of decision making skill in sport: an ecological dynamics perspective”. In: *Perspectives on Cognition and Action in Sport*. January 2016. Nova Science Publishers, Inc., pp. 2–12.

Araújo, D. and K. Davids (2016). “Team synergies in sport: Theory and measures”. In: *Frontiers in Psychology* 7.SEP, pp. 1–13. DOI: 10.3389/fpsyg.2016.01449Team.

Araújo, D., P. Silva, and J. Ramos (2014). “Affordance-based decisions guide team synergies during match performance”. In: *Research in Physical Education, Sport and Health* 3.1, pp. 19–26.

Bradley, Paul S. et al. (2011). “The effect of playing formation on high-intensity running and technical profiles in English FA premier League soccer matches”. In: *Journal of Sports Sciences* 29.8, pp. 821–830. DOI: 10.1080/02640414.2011.561868.

Carling, Christopher and Gregory Dupont (2011). “Are declines in physical performance associated with a reduction in skill-related performance during professional soccer match-play?” In: *Journal of Sports Sciences* 29.1, pp. 63–71. DOI: 10.1080/02640414.2010.521945.

Carrilho, Daniel et al. (Sept. 2020). “Using optical tracking system data to measure team synergic behavior: Synchronization of player-ball-goal angles in a football match”. In: *Sensors (Switzerland)* 20.17, pp. 1–14. DOI: 10.3390/s20174990.

Chow, J. et al. (2013). “The Acquisition of Movement Skill in Children through Nonlinear Pedagogy”. In: *Conditions of Children’s Talent Development in Sport*. Morgantown: FIT, pp. 41–59.

Davids, Keith, Duarte Araújo, and Rick Shuttleworth (2005). “Applications of Dynamical Systems Theory to Football”. In: *Science and Football V: The Proceedings of the Fifth World Congress on Science and Football* i, pp. 537–550.

Di Salvo, Valter et al. (2006). “Validation of Prozone ®: A new video-based performance analysis system”. In: *International Journal of Performance Analysis in Sport* 6.1, pp. 108–119. DOI: 10.1080/24748668.2006.11868359.

Duarte, Ricardo et al. (2013). “Capturing complex, non-linear team behaviours during competitive football performance”. In: *Journal of Systems Science and Complexity* 26.1, pp. 62–72. DOI: 10.1007/s11424-013-2290-3.

Efthimiou, Costas J. (2021). “The Voronoi Diagram in Soccer: a theoretical study to measure dominance space”. In: *arXiv preprint arXiv:2107.05714.*, pp. 1–32. arXiv: 2107.05714.

Fernández, Javier, Luke Bornn, and Dan Cervone (2019). “Decomposing the Immeasurable Sport: A deep learning expected possession value framework for soccer”. In: *MIT Sloan Sports Analytics Conference*, pp. 1–18.

Fonseca, Sofia et al. (2012). “Spatial dynamics of team sports exposed by Voronoi diagrams”. In: *Human Movement Science* 31.6, pp. 1652–1659. DOI: 10.1016/j.humov.2012.04.006.

Fradua, Luis et al. (2013). “Designing small-sided games for training tactical aspects in soccer: Extrapolating pitch sizes from full-size professional matches”. In: *Journal of Sports Sciences* 31.6, pp. 573–581. DOI: 10.1080/02640414.2012.746722.

Gonçalves, Bruno et al. (Sept. 2017). “Effects of Pitch Area-Restrictions on Tactical Behavior, Physical, and Physiological Performances in Soccer Large-Sided Games”. In: *Journal of Strength and Conditioning Research* 31.9, pp. 2398–2408. DOI: 10.1519/JSC.0000000000001700.

Hewitt, Adam, Grace Greenham, and Kevin Norton (2016). “Game style in soccer: What is it and can we quantify it?” In: *International Journal of Performance Analysis in Sport* 16.1, pp. 355–372. DOI: 10.1080/24748668.2016.11868892.

Kim, S. (2004). “Voronoi Analysis of a Soccer Game”. In: *Nonlinear Analysis: Modelling and Control* 9.3, pp. 233–240.

Long, Jed A. and Trisalyn A. Nelson (2013). “A review of quantitative methods for movement data”. In: *International Journal of Geographical Information Science* 27.2, pp. 292–318. DOI: 10.1080/13658816.2012.682578.

McLean, Scott et al. (2018). “The effect of playing formation on the passing network characteristics of a professional football team”. In: *Human Movement* 2018.5, pp. 14–22. DOI: 10.5114/hm.2018.79416.

Memmert, Daniel, Koen A.P.M. Lemmink, and Jaime Sampaio (2017). “Current Approaches to Tactical Performance Analyses in Soccer Using Position Data”. In: *Sports Medicine* 47.1. DOI: 10.1007/s40279-016-0562-5.

Memmert, Daniel, Dominik Raabe, et al. (2019). “A tactical comparison of the 4-2-3-1 and 3-5-2 formation in soccer: A theory-oriented, experimental approach based on positional data in an 11 vs. 11 game set-up”. In: *PLoS ONE* 14.1, pp. 1–12. DOI: 10.1371/journal.pone.0210191.

Memmert, Daniel and R. Rein (2018). “Match analysis, big data and tactics: Current trends in elite soccer”. In: *Deutsche Zeitschrift fur Sportmedizin* 69.3, pp. 65–72. DOI: 10.5960/dzsm.2018.322.

Merlin, Murilo et al. (2020). “Exploring the determinants of success in different clusters of ball possession sequences in soccer”. In: *Research in Sports Medicine* 28.3, pp. 339–350. DOI: 10.1080/15438627.2020.1716228.

Miller, Harvey J. et al. (2019). “Towards an integrated science of movement: converging research on animal movement ecology and human mobility science”. In: *International Journal of Geographical Information Science* 33.5, pp. 855–876. DOI: 10.1080/13658816.2018.1564317.

Müller-Budack, Eric et al. (2019). “”Does 4-4-2 exist?” – An analytics approach to understand and classify football team formations in single match situations”. In: *MMSports 2019 - Proceedings of the 2nd International Workshop on Multimedia Content Analysis in Sports, co-located with MM 2019*, pp. 25–33. DOI: 10.1145/3347318.3355527. arXiv: 1910.00412.

Olthof, Sigrid B.H., Wouter G.P. Frencken, and Koen A.P.M. Lemmink (July 2018). “Match-derived relative pitch area changes the physical and team tactical performance of elite soccer players in small-sided soccer games”. In: *Journal of Sports Sciences* 36.14, pp. 1557–1563. DOI: 10.1080/02640414.2017.1403412.

Pinder, Ross A. et al. (2011). “Representative learning design and functionality of research and practice in sport”. In: *Journal of Sport and Exercise Psychology* 33.1, pp. 146–155. DOI: 10.1123/jsep.33.1.146.

Renshaw, Ian and J. Y. Chow (2019). “A constraint-led approach to sport and physical education pedagogy”. In: *Physical Education and Sport Pedagogy* 24.2, pp. 103–116. DOI: 10.1080/17408989.2018.1552676.

Ric, Angel et al. (2017). “Dynamics of tactical behaviour in association football when manipulating players’ space of interaction”. In: *PLoS ONE* 12.7. DOI: 10.1371/journal.pone.0180773.

Rico-González, Markel et al. (Apr. 2020). *The use of technology and sampling frequency to measure variables of tactical positioning in team sports: a systematic review*. DOI: 10.1080/15438627.2019.1660879.

Riezebos, Mark (2021). “Identifying Play Styles of Football Players Based on Match Event Data”. PhD thesis. Erasmus School of Economics; Erasmus University Rotterdam.

Santana, Juliana (2011). “Representação da área de responsabilidade de jogadores de futebol através do Diagrama de Voronoi”. PhD thesis. Universidade Estadual de Campinas.

Silva, Pedro, Pedro Esteves, et al. (2015). “Effects of manipulations of player numbers vs. Field dimensions on inter-individual coordination during small-sided games in youth football”. In: *International Journal of Performance Analysis in Sport* 15.2, pp. 641–659. DOI: 10.1080/24748668.2015.11868821.

Silva, Pedro, Bruno Travassos, et al. (2014). “Numerical relations and skill level constrain co-adaptive behaviors of agents in sports teams”. In: *PLoS ONE* 9.9, pp. 1–12. DOI: 10.1371/journal.pone.0107112.

Silva, Pedro, Luís Vilar, et al. (2016). “Sports teams as complex adaptive systems: manipulating player numbers shapes behaviours during football small sided games”. In: *Springerplus* 5.Heim 1958, p. 191. DOI: 10.1186/s40064.

STATS (2019). *STATS Playing Styles, Definitions Manual*.

Tallapragada, Phanindra and Senbagaraman Sudarsanam (2017). “A globally stable attractor that is locally unstable everywhere”. In: *AIP Advances* 7.12. DOI: 10.1063/1.5016214. arXiv: 1712.00647.

Tamarit, Xavier (2013). *Periodización táctica vs Periodización táctica*. Valência: MB football.

Yue, Z. et al. (2008). “Mathematical analysis of a soccer game. Part I: Individual and collective behaviors”. In: *Studies in applied mathematics* 121.3, pp. 223–243.

# Chapter 7

# The Finishing Space Value for shooting decision-making in High-Performance Football

Caldeira, N., Lopes, R.J., Fernandes, D. & Araújo, D.

## Abstract

Football players' decision-making behaviours near the scoring target (finishing situations) emerge from the evolving spatio-temporal information directly perceived in the game's landscape. In finishing situations, the ball carrier's decision-making about shooting or passing is not an *individual* decision-making process but a *collective* decision that is guided by players' perceptions of match affordances. To sustain this idea, we collected spatio-temporal information from the match and built a model to quantify the "Finishing Space Value" (FSV). FSV results from the players' perceived affordances, which inform the ball career if: a) is the opponent's target successfully *reachable* from this point where I am (or where a given teammate is)? and, b) can I (or any teammate) shoot with *enough* space (low adversaries' interference)? The FSV was calculated with positional data from 20 high-performance football matches (French Premier League), combining information extracted from Voronoi diagrams with distances and angles to the goal-line. FSV was tested using as a reference the opinion of a "panel of expert" (PE) coaches with a questionnaire presenting 50 finishing situations. Results showed a strong association between the subjective perception scale used by the PE to assess how probable a shot made by the ball carrier could result in a goal and FSV calculated for that same situation ($R^2$ = 0.6706). Moreover, we demonstrate the accuracy of the FSV quantification model to predict coaches' opinions about what should be the "best option" to finish the play. Overall, results indicated that the FSV is a promising model to capture the affordances of the shooting circumstances for the ball carrier's decision-making in high-performance football. FSV might be useful for more precise match analysis and informing coaches in the design of representative practice tasks.

## Keywords

Affordances, Degeneracy, Performance, Team synergies, Voronoi diagrams

## 7.1 Introduction

Being a low-score game, a goal in Football is a "critical event" (Ferreira, 2013) with enormous influence on the match events succession (Nevo and Ritov, 2013) and in its final result (Pratas, Volossovitch, and Carita, 2018). In the present paper, we studied the decision-making processes involved in *finishing situations*, which are of paramount importance for matches' final result

### 7.1.1 Players' decisions and actions are guided by their perceived *affordances*

One of the main objectives of a team with ball possession is to search for a clear opportunity to shoot to the opponent's goal (J. Gréhaigne, Mahut, and A. Fernandez, 2001; Garganta, 2009). As in another *invasion game* (Thorpe, Bunker, and Almond, 1986; Seabra and Dantas, 2006; P. D. Memmert, 2012), the decisions and actions of the football player with the ball (the "ball carrier") are contingent with the dynamics of the interaction between the two teams (Teodorescu, 1984; Travassos et al., 2014). In fact, every player's action is constrained by the actions of all other players (teammates and opponents), which shape the game's *landscape* (Gómez-Jordana et al., 2019). On the football pitch, game landscapes are conceived as "special kinds of spaces, the product of the interaction of human activities and/or environmental elements" (Heras-Escribano and Pinedo-García, 2018)[p2], revealing, for example, the spaces available to run, pass, dribble or shoot.

The game landscape, reveals affordances (i.e., "opportunities for action") (Fajen, Riley, and Michael T. Turvey, 2009) that guide players' decisions (Duarte Araújo, João Ramos, and Lopes, 2016). In Gibson's ecological psychology view, affordances (Gibson, 1979) inform what (and how) actions are possible for each player (Duarte Araújo and Keith Davids, 2011; J. Araujo et al., 2019), based on their perceptual *attunement* to the affordances of the game landscape (Reed, 1996). From this ecological dynamics perspective, psychological processes, such as perception, action and decision-making, should be understood at the *environment-athlete* system level (Duarte Araújo, Keith Davids, and Hristovski, 2006), where *perception* and *action* are tightly intertwined and cannot be separated (Gibson, 1979). Understanding performers' actions as inseparable from the environment they perceive, ecological approaches to decision-making do not seek explanations for human behaviour inside of the individual, e.g., on internal mental mechanisms and referents from where the appropriate (rational) decision could be retrieved (Duarte Araujo and Renshaw, 2010). From an ecological dynamics perspective, decision-making behaviours are transitions in modes of action (e.g., from running to dribbling) which emerge from the *performer–environment* system to achieve a more attractive (stable) state of behaviour towards a task goal (Duarte Araujo and Renshaw, 2010).

### 7.1.2 Collective decisions in finishing situations

In *invasion games*, such as football, both teams have mutually exclusive goals (Thorpe, Bunker, and Almond, 1986; J. Gréhaigne, Mahut, and A. Fernandez, 2001), where players of a given team need to cooperate to achieve the goal of their team in the match. Team players' actions are thus *joint* or coordinated actions (Fajen, Riley, and Michael T. Turvey, 2009) leading to the appearance and disappearance of match affordances (e.g., opening for a pass) that are collectively perceived (Pedro Silva et al., 2013; D. Araújo, P. Silva, and J. Ramos, 2014). Consequently, the action of every individual player cannot be seen as isolated, but as the result of team synergies (D. Araújo and K. Davids, 2016) that continuously are formed and dissipate as the game landscape of affordances changes (Duarte Araújo, Brito, and Carrilho, 2022). Therefore, we argue that decision-making processes in football finishing situations are not only about *who* should be the player to shoot in a given moment of the game (D. Araújo and K. Davids, 2016). Instead, decisions emerge from a collective process, synergizing the actions of multiple players (Duarte Araújo, Brito, and Carrilho, 2022). This collective process of decision-making, is primarily constrained by the team's match goal (Button et al., 2013), and emerges from players' perception of the game landscapes and its possibilities for action, i.e., on the game *shared* affordances that could invite players to act (e.g. to shoot or to pass) (Gibson, 1979; Pedro Silva et al., 2013; D. Araújo, P. Silva, and J. Ramos, 2014). This cannot be pre-determined (e.g., by the coach before the match, attributing a particular static role to a given player).

Football players' decision-making behaviour should be seen as essentially emergent ecological *collective* processes (Duarte et al., 2010; Duarte Araújo, Brito, and Carrilho, 2022). The behaviours of each player influence and are influenced by the behaviours of the others, establishing a causal circularity typical of synergies (M. T. Turvey, 2007). For example, the ball carrier's decision-making on whether to shoot or not (e.g., passing to a better-positioned teammate) emerges from their perception of a landscape that is shaped by the (joint) action of all elements on the pitch (Pol et al., 2020). Importantly players' decision-making behaviour in finishing situations is guided by affordances of the match that are collectively perceived. Moreover, perceiving an affordance in the performance environment is predicated on each player's action capabilities (D. Araujo, M. Dicks, and K. Davids, 2019). As Heras-Escribano and Pinedo-García (Heras-Escribano and Pinedo-García, 2018) argue "since the *value* of the surrounding environment is neither intrinsic to the environment nor in the eye of the beholder", there is "no sharp distinction between the objective, agent-independent character of affordances and the subjective, agent-dependent character of affordances" (Heras-Escribano and Pinedo-García, 2018)[p4]. In fact, based on the mutuality of performer–environment system, the information in a given environment informs about its affordances, and it is necessary to guide actions (Heras-Escribano and Pinedo-García, 2018). Therefore, in this paper, spatio-temporal affordances for players were captured by matches' positional data to understand the collective decisions involved in a set of football finishing situations (Jokuschies, Gut, and Conzelmann, 2017).

### 7.1.3 Developing a method to capture spatial affordances in finishing situations

In this paper, we hypothesized that the information captured from the match positional data can be used to formally quantify players' *affordances* in football finishing situations(Aguilera and Heras-escribano, 2019). The information of the game environment informs players about the relevant modes of action to maintain or to change (e.g., to shoot or not to the opponent's goal). Nevertheless, more than simply treating action possibilities as binary categories, we agree with Franchak and Adolph (Franchak and Adolph, 2014) when they propose the quantification of affordances through *probabilistic functions* to describe the *likelihood of success* for every parameter of a given environment (Franchak and Adolph, 2014). This perspective will be used in this paper to quantify a set of *affordances functions* (Franchak and Adolph, 2014), establishing the *likelihood of success* that can express players' affordances. From our point of view, the distances to the goalposts and as well as that among players, allow for the quantification of the open spaces around each player, capturing players' affordances and coaches' perceptions of players' affordances.

#### How *reachable* is the opponent's goalposts ?

When football players perceive shooting possibilities, they perceive the distance to the opponent's goalposts and how *reachable* it is from their *location* on the pitch (Fajen, Riley, and Michael T. Turvey, 2009; Passos, Duarte Araújo, and Keith Davids, 2016). Therefore, a method to explain players' decision-making in a finishing situation needs to start by considering the location of each player in relation to the opposite goal. The perception of how reachable the goal is could then be assessed through the computation of the *success ratio* of a shot made from a given pitch location (i.e., the *distance* and *angle* to the opponent's goal) (Link, Lang, and Seidenschwarz, 2016). Importantly, Pollard and colleagues (Pollard, Ensum, and Taylor, 2004) concluded that for each additional yard between the player and the goal, the probability of scoring decreased by 15%; whilst for each angle degree, there was a decrease of 2%. These two parameters (distance and angle) enter in the model of the *affordances functions* (Franchak and Adolph, 2014) used to estimate the probability of a shot resulting in a goal (see the heatmap graph 7.17, in the Appendix). This is similar to the model to compute the "dangerousity" of a shot by Link and colleagues (Link, Lang, and Seidenschwarz, 2016), where one of its components is the *Zone* that represents the probability (danger) of a goal being scored from the location of the ball carrier, considering player's distance to the goal (see the heatmap graph 7.18, in the Appendix). Despite the differences between the existing models, they converge in that the closer the ball carrier is to the opponent's goal, the greater the probability of scoring (Pollard, Ensum, and Taylor, 2004; Link, Lang, and Seidenschwarz, 2016; Pratas, Volossovitch, and Carita, 2018; Rowlinson, 2020). However, in many finishing situations, an affordance to shoot can cease to exist, due to the player's location towards the opponent's goal and the movement of opponent players in the surrounding pitch location.

**Is the space to shoot "broad" enough?**

The context of the game does not always allow the ball carrier to shoot to the goal, but this is not always clear in different models. For example, for Pollard and colleagues (Pollard, Ensum, and Taylor, 2004), address the question of "whether or not the person taking the shot had space" with a binary system that "quantified by 0 if there was an opponent within one metre, and 1 if not". That is, as long as there was an opponent less than a meter away, this model completely excluded the chances of scoring a goal from a player who was in a given location on the field. Moreover, there was no impact on the calculation if the closest opponent was at any further distance (Pollard, Ensum, and Taylor, 2004). Similarly, the model of "dangerousity" of a shot proposed by Link and colleagues (Link, Lang, and Seidenschwarz, 2016), considers that the *Zone* is not enough to characterize the game's landscape and the spatio-temporal context where players are embedded. They situate each player in the game's context, by including other parameters such as Control, Pressure and Density (Link, Lang, and Seidenschwarz, 2016).

This concern with the analysis of the *context* is somehow present in several models that express the *likelihood of success* of a shot and that are usually denominated as *expected goals* (xG) models (Eggels, 2016; Rathke, 2017; Spearman, 2018; Pardo, 2020; Rowlinson, 2020; Anzer and Bauer, 2021; Cavus and Biecek, 2022). Despite the different computational procedures behind (involving diverse methods of *artificial intelligence*), all xG models are based on a *success ratio* (number of goals/number of shots) that expresses the probability of scoring, being more accurate the more data exist for those same circumstances. For this reason, in addition to often addressing quite diverse databases (different competitions, levels, ages, genders, etc.), the majority of the xG models are based on event data (more frequently available) and not positional data from players' tracking (Rowlinson, 2020). Consequently, the contextual information that provides the training of the machine learning algorithms in xG models is more centred on the type of play (e.g., free kicks or open plays) or the event that originates the goal opportunity (e.g., dribble or long pass) (Eggels, 2016), than in the spatial characteristics of the game's landscape. For example, Cavus and Biecek (Cavus and Biecek, 2022) recently proposed a model of xG where the ”contextual” information is composed of categorical variables about the game's circumstances (e.g., home or away match, game's minute) and only has two continuous variables: the distance and angle to the goal. Therefore, albeit indicating the shots' *likelihood of success*, the xG algorithms merge in different degrees this type of notational information (Vilar et al., 2013) with information captured in the game's landscape, without presenting players' affordances about their ”space” to shoot (Rowlinson, 2020). This led the present study to differently consider parameters and mathematical procedures that in previous models did not clarify how different players' affordances were integrated (e.g. the ball carrier's space to execute the shot and/or the proximity of opposition). This is aligned with Lucey and colleagues (Lucey et al., 2014), who coincidentally argued that the ”goal likelihood” can be calculated with increasing accuracy when the xG integrates different game's landscape *contextual* parameters (e.g., the proximity of the defenders) beyond the simple players' location on the pitch. Finally, the xG model proposed by Rowlinson (Rowlinson, 2020) integrated the computation of Voronoi diagrams (VD) to assess the *open space* around some players. However, in this xG model, the *Voronoi cell areas* (VA) were calculated only for the ball carrier and opposing goalkeeper.

In the present study, we aimed to follow this suggestion of Rowlinson (Rowlinson, 2020) and test if it could be upgraded in a model that considers not only the VA of the ball carrier and the opposing goalkeeper but all the players on the pitch. We hypothesize that this procedure can determine the *open spaces* around each player and assess if the game's landscape offer possibilities (affordances) for players to shoot from their location on the pitch.

### 7.1.4 The “Finishing Space Value” (FSV) model for decision-making to shoot

To understand how the spatial affordances of the match influence the ball carrier's decision about *who* should shoot on goal in a finishing game situation, we delimit the present model to open-plays (e.g., set-pieces are not included) and to shots with the feet (e.g. shots with the head are not included).

As mentioned above, distance and angle to the opponent's goal and the open space around players are key constraints for understanding shooting, which can be perceived as affordances for the ball carrier, i.e., if the opponent's goalpost is *reachable* and if the space is *broad* enough to shoot. Consequently, the “Finishing Space Value” (FSV) model quantitatively values the occupation of a given space when in finishing situations.

This is not the approach followed by the majority of Expected Goals (xG) models because these are essentially based on event data and on “contextual” information that does not come from the game dynamics (Anzer and Bauer, 2021; Cavus and Biecek, 2022). These are the main reasons that motivate us in searching for a FSV model that can objectively quantify some spatial affordances of the football game's landscape.

The FSV model is closer to Fernandez and colleagues' “Expected Possession Value (EPV)” (Fernández, Luke Bornn, and Dan Cervone, 2019; Fernández, Luke Bornn, and Daniel Cervone, 2021). Their model, inspired by the basketball studies of Cervone and colleagues (Daniel Cervone et al., 2016), captures the likelihood of a team scoring or conceding the next goal at any time instance. Aiming to provide "soccer practitioners with the ability to evaluate the impact of observed and potential actions, both visually and analytically", the "EPV expression is decomposed into a series of subcomponents that model the influence of passes, ball drives and shot actions on the expected outcome of a possession" (Fernández, Luke Bornn, and Daniel Cervone, 2021)[p1389]. Moreover, the EPV generally "incorporates the dynamics of the 22 players and the ball through tracking data" (Fernández, Luke Bornn, and Daniel Cervone, 2021)[p1389]. However, for finishing situations there are two main differences with our model. First, for shooting, the EPV model is calibrated (i.e., trained) with event data to calculate a "goal expectation" (xG) from the ball location (distance and angle between the ball location and the goal). The contextual categorical variables used by EPV are irrelevant to our model because FSV addresses exclusively open-plays and shots with the feet. Second, there is a conceptual difference about the definition of a time frame to compute players' *free spaces* around them. To Fernandez and colleagues (Fernández, Luke Bornn, and Daniel Cervone, 2021), the "free space" of each player is based on his/her "reachability surface", i.e., the pitch surface that a player can cover in a certain *time lag* (in this case in one second), given his direction and velocity vector. All the pitch regions that cannot be reached during this time frame are excluded (see also (Caetano et al., 2021)). Such player's "reachability surface" is difficult to apply to the diversity of finishing situations (e.g., counter-attack or positional attack). We argue that the game's context that affords to shoot is a consequence of players' perception of the distances to their opposing neighbours in a given instant. For example, if the nearest defender is far enough it is possible to delay the shooting decision, not because of the "reachability surface", but because of the distance to the opponent. Consequently, it is our contention that "free spaces" resulting from the distances among players over time can be more accurately captured through "Voronoi diagrams" (VD) and their metrics than from the models using "reachability surface" (Fernández, Luke Bornn, and Daniel Cervone, 2021; Caetano et al., 2021) with a fixed time lag. Moreover, in "finishing situations" players increase the simulation of trajectories (Raab, 2010; Link and Hoernig, 2017). Such "simulations" (Mateus, 2005) imply that any model has to be updated at each time instant as "soccer players try to confuse each other with unexpected changes in velocity" (Baysal and Duygulu, 2016)[p1350]. Therefore, if a model needs to be updated at each time instant, it remains evident how can be difficult to previously define the time lag that is needed to compute the "reachability surface" (Fernández, Luke Bornn, and Daniel Cervone, 2021; Caetano et al., 2021).

To compute "free spaces" around players without fixed time lags, Taki and Hasegawa's model computed players' "dominant regions", i.e, the region that could be reached before any other player if all players keep their trajectory and speed (Taki and J. i. Hasegawa, 2000; Taki and J.-i. Hasegawa, 2000). The concept of "dominant region" (Taki and J. i. Hasegawa, 2000; Taki and J.-i. Hasegawa, 2000) is inspired by the works of Okabe and colleagues on "Voronoi Diagrams" (VD) (Okabe, Boots, and Sugiharam, 2000) which are based on the distances between each player and their neighbours in a given instant (not considering players' trajectories or speeds). More exactly, VD are computed from the *Delaunay Triangulation* that result from the distances between each point (player) to its nearest neighbours (Chiu, 2003). In each VD, the *Voronoi cell* (VC) of each player is then constituted by all points of the pitch closer to that player than to any other (Kim, 2004). Therefore, the VC is a “dominant region” exclusively based on Euclidean distances, independently of player’s speed and direction (Rein, Raabe, and D. Memmert, 2017), overcoming the need to assume a linear maintenance of player’s trajectory and speed.

Even if VD based-models seem to be simplistic, any of the more sophisticated models of “dominant regions” could overcome the VD limitations (Efthimiou, 2021). In fact, “players are moving around with different velocities and possess inter-individual maximum running velocities and acceleration capabilities” (Rein, Raabe, and D. Memmert, 2017)[p179]. The problem with the models based on fixed parameters and linearity is that they are not adjusted to each situation (e.g., positional attack vs counter-attack), players’ individual constraints and contexts. This perspective is also defended by Rein and colleagues (Rein, Raabe, and D. Memmert, 2017)[p179] when they verified that the more complex running models introduced by Taki and Hasegawa (Taki and J. i. Hasegawa, 2000) “did not show any major differences in results compared to those reported by Fonseca and colleagues (Fonseca et al., 2012) who used a standard Voronoi-diagram”.

For all these reasons, the FSV model that is tested in this paper includes a component based on standard VD to capture the affordances (Gibson, 1979) perceived as “shoot-on-able” free spaces around players towards the goalposts.

VD are computed from the distances between each player and *all* other players on the pitch. This implies that, to situate a player within his/her Voronoi cell (VC) and to contextualize the “free space” around him/her, is important to include the distance between a given player and the nearest border of his/her VC. Thus, the FSV model includes the distance between each player and his/her nearest defender as well as between him/her and the opponent’s goalposts.

In sum, from an ecological dynamics theoretical framework (Gibson, 1979; Duarte Araújo, Keith Davids, and Hristovski, 2006) players’ decisions emerge from the affordances perceived in the game’s landscape. The aim of the present study was to test the Finishing Space Value (FSV) model that captures the *affordances* perceived in finishing situations. The FSV is composed of two main parameters that measure how much *reachable* is the opponent target from where the ball career or his/her teammate is and, how *broad* enough is the ball career’s (or his/her team-mate) space to shoot from that location (Fajen, Riley, and Michael T. Turvey, 2009; Pedro Silva et al., 2013). The FSV model includes in a single value the two mentioned parameters capturing the *value* of occupying a certain spot on the pitch in finishing situations.

## 7.2 Materials and Methods

### 7.2.1 Data sources

Three data sources are used in this paper with different aims: a) one database with the subjective opinion of a ”Panel of Experts” (PE) about 50 finishing situations; and b) two databases used to estimate the parameters of the “Finishing Space Value” (FSV) model.

### Panel of expert football coaches

Players' decisions happen in a particular game context and time making it impossible to identify the exact constraints that make every decision emerge. Consequently, we test the FSV model using as a reference the opinions of expert football coaches' about the game's landscape in the instant of the shoot and what they considered being the "best decision" in that situation. We used two statistical approaches based on the Brier Score (see 7.2.3 that measures the accuracy of probabilistic predictions:

1. the first approach compares the FSV of each player with all the others to elect the FSV of the player with the higher value among them; and

2. a second approach compares the FSV of each player only if the ball carrier does not achieve a certain threshold of probability to be him/her the one who shots: "The worst mistake we can make in a finishing situation is to not take the shot when we are close enough to the opposing goal and with space to do it" (Queiroz, 1986). It assumes that there is a threshold in which the best option is for the ball career to shoot.

The FSV model was tested against the opinion a "panel of expert(s)" (PE) football coaches. The PE was composed of 10 professional Portuguese football coaches, all holding a UEFA PRO license and with a minimum of 10 years of high-level football coaching experience, in the Portuguese 1st league.
The PE opinion was obtained through a questionnaire, applied at the beginning of the 2022-2023 season (August and September of 2022). The questionnaire had 50 finishing situations randomly selected from a set of 20 high-performance football matches (French Ligue 1), from the 2019-2020 season, as described below in b) of section 7.2.1.
To build the survey, each situation was illustrated by an image (as exemplified by Figure 7.1), corresponding to the instant of a shot, where players were identified with letters A to D (the ball carrier was always identified with the letter A). The question for the PE was:
*"In this image, Player A took the decision to shoot to the goal.*
*a) Please evaluate, on a scale from 1 to 10 (where 1 is "not at all likely" and 10 is "highly likely"), what you consider to be the probability to score a goal from that specific shot of player A".*
*b) Do you think that player A chose "the best option" in that situation, or it would be preferable to pass to one of his teammates (B, C and D)?".*
*If you consider that the play should not be finished immediately, as neither player A nor any of his colleagues (B, C or D) were in a good position to score immediately (i.e., by shooting or through a single assistance pass), please choose option "E".*

### Data sources for the FSV model

The estimation of the FSV components was obtained from a database that address two different aspects:

a) Assign a value to the pitch *locations* (defined by distance and angle to goal) corresponding to the

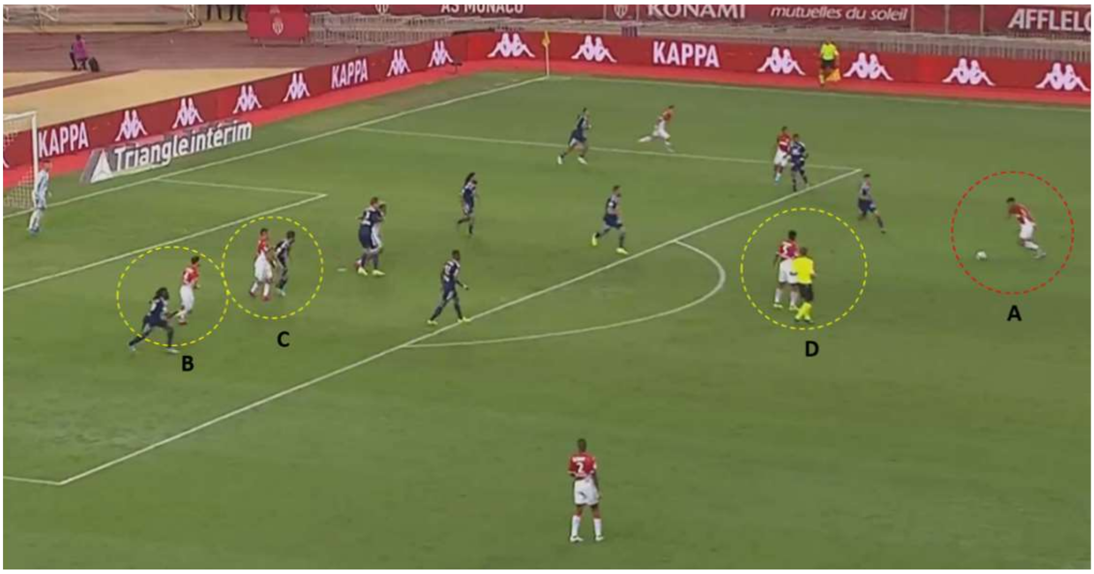



**Figure 7.1:** Illustrative image of a finishing situation presented in the survey to the “panel of expert” football coaches. Player ”A” is the ball carrier who shot and the players marked with B, C and D are his colleagues that we consider as possible passing options.

probability of scoring from a shot made from that location. This was obtained from a database composed of 283 games, from the Ligue 1 and Champions League competitions, played between 2016 and 2020. In the 283 matches, a total of 5294 shots made with players' feet and from open play situations were observed, from which 543 goals were scored. The database was provided by the company STATS and computed using their semi-automatic tracking systems (as validated in (Di Salvo et al., 2006)).

b) Assign a value to the free spaces around each player. These were obtained using Voronoi diagrams (VD) from a subset of 20 football matches of the first database, randomly selected from the 2019-2020 season. In these 20 matches, a total of 311 shots were selected, corresponding to shots made with the players' feet, in opening play situations, and where the ball carrier had, at least, two other teammates as passing possibilities in the offensive last third of the pitch (i.e., to $x \geq 70m$, the opponent's goal is at $105m$). Finally, from these 311 shots, 50 shots were randomly selected for the questionnaire presented to the Panel of Experts.

### 7.2.2 Data processing

The FSV quantification for each player was calculated for each finishing situation (see example in Figure 7.1). Thus, for each player (A, B, C and D), the FSV model integrates three parameters: a) the “Player Location” (PL); b) the “Player Relative Area” (RVA); and c) the “Player Relative Position” (RVP). The PL is the location of each player, considering only the distance and angle of each player to the centre of the opponent's goal line. The two other parameters are taken from the Voronoi diagrams (VD) computed from the distances among all players on the pitch and forming the relative area (RVA) and the relative position (RVP) of each player within the Voronoi cell. Therefore, the FSV defined in arbitrary units (AU), was calculated by the multiplication of these three parameters, i.e.:

$$FSV = PL \cdot (RVA \cdot RVP)$$

Therefore, the parameters used in the FSV computation correspond to:

1. The "*Player Location*" (PL), computed as the probability of getting a goal from a shot at a given position (see Figure 7.16 in the Appendix), considering two sub-components: a) the distance; and b) the angle of each player in relation to the opponent's goal (described in 7.2.2).

2. The "*Player Relative Voronoi Area*" (RVA), capturing the space around each player in a Voronoi diagram (VD), corresponding to the respective cell area and considering its specific location in the *effective playing space* (EPS) (described in 7.2.2).

3. The "*Player Relative Voronoi Positioning*" (RVP), depending on the player's distance to their nearest opponent towards the goal line (described in 7.2.2).

For all three parameters, a similar process of fitting a polynomial curve to the database data is used, illustrated in figures 7.9 to 7.15 in the Appendix.

#### The Player Location (PL)

The Player Location (PL) quantifies the probability to score in a shot made from a specific location on the pitch, considering the *distance* and the *angle* to the centre of the goal line. Figure 7.2 shows the outcome of the 5294 shots in the database (543 goals scored in blue (10.26%), 4751 shots without goal in red) given the distance and angle to the goal.

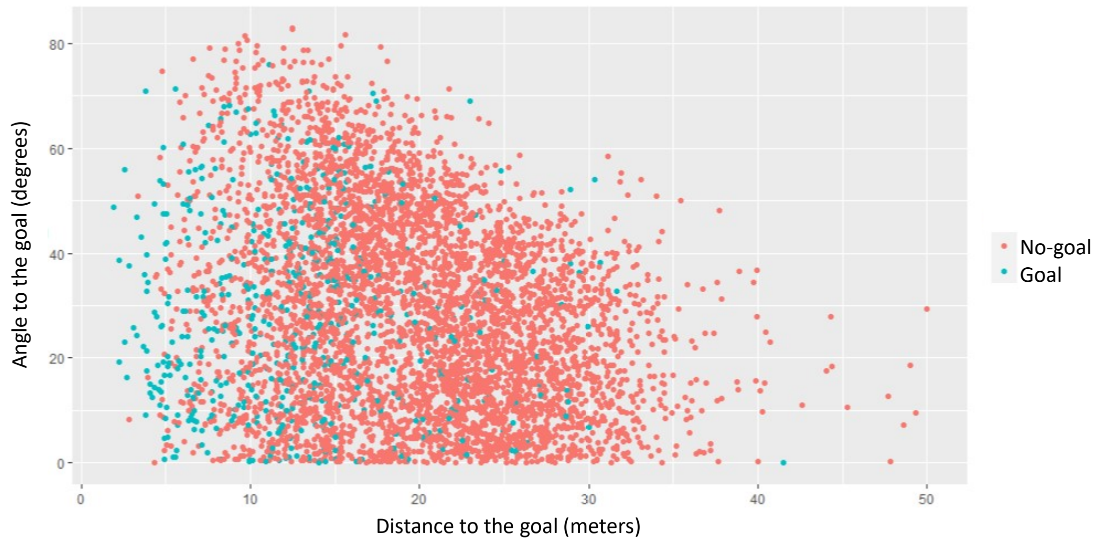



**Figure 7.2:** Shots with (blue) and without (red) scoring according to distance and angle to goal.

This data was used to estimate the parameters of a polynomial equation for the scoring probability given the positional coordinates (distance and angle) of a player. Thus, the probability (in %) to score varies according to the value $x$ corresponding to the PL distance (PLd), in meters, to the centre of the opponent's goal line, as:

$$PLd = -0,0107x^3 + 0,7061x^2 - 15,3620x + 115,1100$$

The Figure 7.2 shows also how PL angle to the centre of the goal, influences the probability to score. In this case, the probability (in %) to score (y) varies according to the value x corresponding to the PL angle (PLa), in degrees, to the centre of the opponent's goal line, as:

$$PLa = -0,0129x^2 + 0,0347x + 79,7020$$

The PL component was then calculated from the multiplication of these two polynomial equations obtained from the players' distance and angle to the centre of the opponent's goal line:

$$PL = PLd \cdot PLa$$

The PL probabilities can be visualized in Figure 7.16 of the Appendix and compared with similar approaches made by Pollard and colleagues (Pollard, Ensum, and Taylor, 2004) (7.17) and Link and colleagues (Link, Lang, and Seidenschwarz, 2016) (7.18).

#### The Player Relative Voronoi Area (RVA)

To assess players' context in the game's landscape, the Voronoi cell areas (VA) corresponding to each player, were calculated from the positional data of the matches' database, using a set of computer routines in Excel (VBA) to automate the set of procedures described by Kim(Kim, 2004). The VA of each player is the absolute area of each Voronoi cell (in m2). However, players' absolute VA must be placed in the proper context. In fact, the circumstance that a player is *inside* or *outside* the *effective playing space* (EPS) (J. F. Gréhaigne, Bouthier, and David, 1997) strongly influences the VA absolute value. As exemplified in Figure 7.3, in a Voronoi diagram it is possible to identify four possible regions of the EPS where a player can be in a given instant:

a) Voronoi cells inside the EPS (INS), i.e., that do not contact any of the outer lines of the pitch or with the goalkeepers' cells (e.g., the white shaded cell in Figure 7.3).

b) Voronoi cells outside and in front of the EPS (OUT_F), which contact only the opposing goal line or the opposing goalkeeper's Voronoi cell (e.g., the yellow shaded cell in 7.3).

c) Voronoi cells outside the EPS, which contact only the pitch sideline(s) (OUT_S) (e.g., the red shaded cell in Figure 7.3).

d) Voronoi cells outside the EPS that contact, simultaneously, the opposing goal line or the cell of the opposing goalkeeper (front) and at least one of the pitch outside lines (OUT_S_F) (e.g., the blue shaded cell in Figure 7.3).

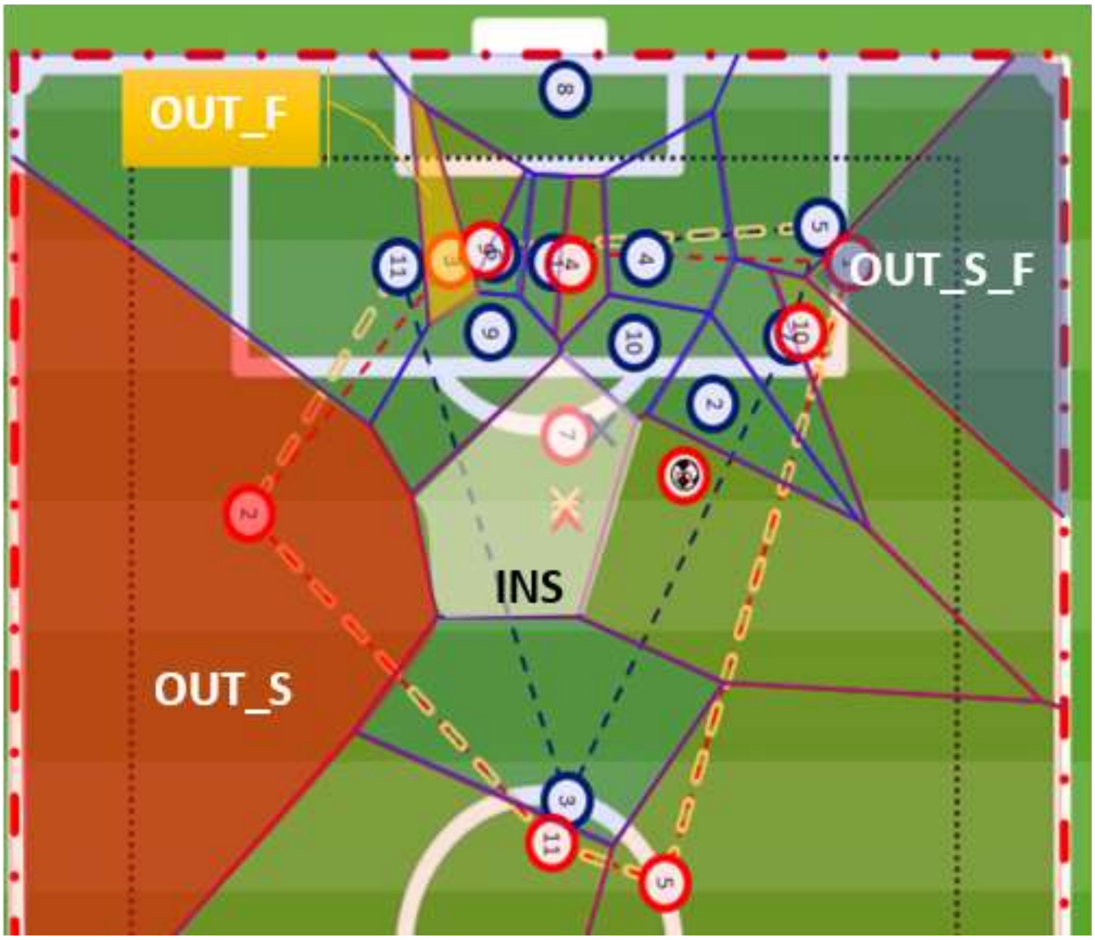



**Figure 7.3:** Player's Voronoi cells in four different regions of the effective playing space (EPS)
*Note:* Voronoi diagram with the positions of players from both teams: the "in ball possession" team (red circles) and the "out of ball possession" team (blue circles). The Effective Playing Space (EPS) is limited by the yellow dashed line. Four regions were identified: inside the EPS (INS) or outside the EPS, in this case considering three different situations (i.e., OUT_S, OUT_F; OUT_S_F).
Crosses indicate the match (yellow) and the team's centroids (red and blue). See text for details.
1

The modulation effect of the RVA parameter is obtained by comparing the *actual* Voronoi cell area (VA) value of each player to the *expected* Voronoi Area (VAe) for that pitch location. Using the average values of players' Voronoi cell areas (VA) in the matches database it was possible to calculate the players' expected Voronoi Area (VAe), considering players' distance to the centre of the opponent's goal line ($x$) in four different regions of the EPS (as shown in Figure 7.3). Tables 7.1 and 7.2 presents for each of the four EPS regions, the equation estimated for the players' *expected* Voronoi Area (VAe). Different equations are obtained for the *ball carrier* (BC) and for his teammates *without the ball* (NB) as these correspond typically to different relations between the ball carrier and other players (e.g., ball carrier pressure).

| *EPS Region* | *Formulas to the Ball Carrier (BC)* |
|---|---|
| INS | $= -0,0035x^3 + 0,2125x^2 - 2,0532x + 24,5210$ |
| OUT_F | $= -0,0630^2 + 5,3921x + 6,4489$ |
| OUT_S | $= 0,0181x^3 - 1,9781x^2 + 61,8270x - 335,7300$ |
| OUT_S_F | $= 0,0262x^3 - 2,1278x^2 + 47,7160x + 11,4520$ |

**Table 7.1:** Ball Carrier's *Expected Voronoi Area* (VAe) in function of the *distance* to the centre of opponent's goal line (x) for each *region* of the Effective Playing Space (EPS)

| *EPS Region* | *Formulas to the BC's teammates (NB)* |
|---|---|
| INS | $= -0,0057x^3 + 0,3018x^2 - 1,5952x + 14,1360$ |
| OUT_F | $= -0,1019x^2 + 8,1389x - 9,8798$ |
| OUT_S | $= 0,0118x^3 - 1,7250x^2 + 61,1630x - 201,0100$ |
| OUT_S_F | $= 0,0361x^3 - 3,0145x^2 + 77,3510x - 136,5000$ |

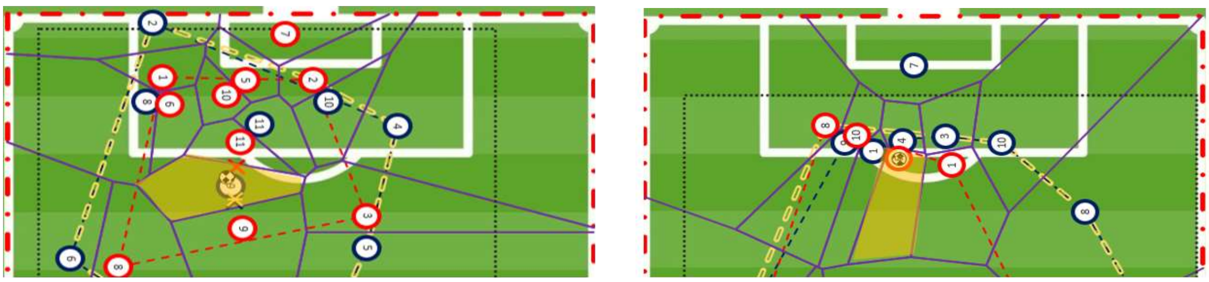
**Table 7.2:** Teammates' of the ball carrier without the ball *Expected Voronoi Area* (VAe) in function of the *distance* to the centre of opponent's goal line (x) for each *region* of the Effective Playing Space (EPS)

As our purpose was to use VD to measure if players had *enough* space to shoot, their VA absolute values measured in a given instant had to be transformed in relative values. Accordingly, we assess if players' VA at each shot, with its distance to the goal and EPS zone, were smaller or larger than the *typical* (expected) VA at that distance and EPS zone. To this end, we *divided* players' *actual* VA measured in each finishing situation (VAr), by the VA that a player in the same contextual circumstances was *expected* to have (VAe). Thus, the Player Relative Voronoi Area (RVA) is calculated by:

$$RVA = \frac{VAr}{VAe}$$

#### The Player Relative Voronoi Positioning (RVP)

The third parameter of the FSV model was introduced to take into account the player's position within the Voronoi cell (RVP). For the ball carrier or his/her teammates, the perception that they have *enough* space to shoot is not only a consequence of their Voronoi cell area but also of their relative position inside the respective cell. This is exemplified in the two diagrams in Figure 7.4, where two very different positions are represented in Voronoi cells with almost identical areas (in $m^2$).



**(a)** Larger distance to closest defender   **(b)** Smaller distance to closest defender

**Figure 7.4:** Voronoi diagrams with different distances to the nearest defender

Figure 7.4 shows that, although in both situations the Voronoi area (in $m^2$) of the ball carrier (highlighted in yellow) is similar (around $40m^2$), the distance from the nearest opponent (between him and the opponent's goal) is different in diagrams 7.4a (larger) and 7.4b (smaller). This means that the space to shoot for the player in diagram 7.4a can be bigger than the one for the player in diagram 7.4b. Thus, even in identical regions of the EPS (inside), the player's positioning within the Voronoi cell is influenced by his distance to their nearest opponents. To assess players' space to shoot, it is important to consider the distance between each player and the nearest opponent towards the goal line. The differences in the players' relative Voronoi cell positioning (RVP) are expressed mathematically by the natural logarithm (LN) of the distance between each player of the in-possession team and his nearest opponent. To exemplify the impact of RVP in the FSV model, when a player has an opponent at a distance smaller than 1 meter, the application of the LN will imply a negative FSV value. This reflects the high pressure potentially placed by that opponent in that specific situation, thus reducing the value of the space to finish the play with a shot.

### 7.2.3 Statistical analysis methods

How the "Finishing Space Value" (FSV) model captures the affordances to shot in finishing situations was assessed by comparing it with the opinions of a "Panel of Expert" (PE) football coaches. In other words, the probability of coaches choosing each option in each finishing situation was compared with the respective FSV quantification for each player in each of the presented finishing situations (see example in Figure 7.1). Three statistical tools were used:

a) A linear regression between the FSV and the scale used by the PE, on how probable a shot made from Player A (i.e., the ball carrier) in each situation could result in a goal.

b) The Gwet AC1 statistic (Amon, Vrzakova, and D'Mello, 2019; Bühn et al., 2021), to assess the inter-rater reliability coefficient, i.e, the degree of agreement among the coaches of the PE when they choose one option of $C_M = \{A, B, C, D, E\}$ for each of the 50 finishing situations of the questionnaire. The AC1 statistic is computed using:

$$AC1 = \frac{p_a - p_{e_\gamma}}{1 - p_{e_\gamma}} \tag{7.1}$$

Where $p_a$ is the overall agreement probability between experts and $p_{e_\gamma}$ is the chance-agreement probability (i.e., the probability that the agreement between experts is due to chance), given by:

$$p_a = \frac{1}{N}\sum_{i=1}^{N} p_{a_i} = \frac{1}{N}\sum_{i=1}^{N}\sum_{j=1}^{M_i}\frac{e_{ij} - 1}{R(R-1)} \tag{7.2}$$

$$p_{e_\gamma} = \frac{1}{M-1}\sum_{j=1}^{M}\pi_j(1-\pi_j) \tag{7.3}$$

Here, $p_{a_i}$, is the agreement probability in situation $i$; $R$, is the total number of experts; $N$, is the number of finishing situations analysed; $M_i = |C_{M_i}|$, is the number of categories (i.e., different options considered by the experts) in situation $i$; $e_{iq}$, is the number of experts that selected the $q^{th}$ option for the $i^{th}$ situation and $\pi_j$ is the probability that an expert selects option $j$,

$$\pi_j = \frac{1}{N}\sum_{i=1}^{N} r_{ij} = \frac{1}{N}\sum_{i=1}^{N}\frac{e_{ij}}{R} \tag{7.4}$$

c) A multiclass Brier Score (BS), to measure the accuracy of the FSV model to predict the choices of the "Panel of Experts" (PE). That is, the multiclass BS compares, in each finishing situation, $i$, the fraction, $r_{ij}$, of the PE that chose option $j$, with the probability, $p_{ij}$, assigned by an FSV-based model. Each situation, $i$, contributes to the overall BS with $BS_i$, given by:

$$BS_i = \frac{1}{2}\sum_{j=1}^{M}(p_{ij} - r_{ij})^2 \tag{7.5}$$

$$BS = \frac{1}{N}\sum_{i=1}^{N} BS_i \tag{7.6}$$

In the FSV-based probabilistic models each option, $j$ in $C_M$ is characterized by the stochastic variable $X_{ji}$ in situation $i$. Two different approaches are used:

(a) **FSV, approach I**, where the probability, $p_{ij}$, that option $j$ is selected in situation $i$ is given by:

$$p_{ij} = pd_{ij} = P(X_{ji} > \max\{X_{mi}, \cdots, X_{ni}\}) \tag{7.7}$$

that is, the probability that the value assigned to option $j$ is bigger than any of the other options. For option $A$ (ball carrier) and $C$ to $D$ (teammate) $X_{ji}$ is described by a $\chi$ distribution with parameter $k_{ji}$ defined by the FSV value corresponding to that option and situation, i.e., $X_{ji} \sim \chi(FSV_{ji})$. Is important to stress that, "Option E" corresponds to not choosing any of the players A to D, thus, there is no FSV for this option. Consequently, the probabilistic model for "Option E" is defined by fitting a skewed normal distribution to the players' (A to D) FSV values when "Option E" is selected (see Figure 7.20 in the Appendix).

(b) **FSV, approach II**, where "Option A" is considered differently from all other options, as it is considered that if the ball carrier ("Option A") has a "minimum" FSV value then he/she should shoot. The "minimum" FSV value is described by a normal distribution, $Xt_{Ai} \sim \mathcal{N}(\mu, \sigma^2)$, with $\mu, \sigma^2$ fitted to the ball carrier (A) FSV values when option A is selected (see Figure 7.21 in the Appendix). Consequently, the probability for option A is given by:

$$p_{Ai} = pt_{Ai} + (1 - pt_{Ai})pd_{Ai} \tag{7.8}$$

The first term is associated with the probability of A's FSV reaching a "minimum" value, i.e., $p_{Ai} = P(Xt_{Ai} < FSV_{Ai})$ and the second term of is associated to the probability of A's FSV value being bigger than all other options ($pd_{Ai}$ defined as in Eq. 7.7). For the remaining options (B to E), $p_{ji}$ is defined by:

$$p_{ji} = (1 - pt_{Ai})pd_{ji} \tag{7.9}$$

In order to assess the "quality" of the two FSV versions, they can be compared with a reference (blue line in Figures 7.7 and 7.8). We used as reference a model where for all situations the probability that an expert selects option $j$ is used, i.e., $p_{ij} = \pi_j$ and consequently:

$$BS_{ref} = \frac{1}{2N}\sum_{i=1}^{N}\sum_{j=1}^{M}(\pi_j - r_{ij})^2 \tag{7.10}$$

## 7.3 Results

### 7.3.1 Comparative analysis of the ball carrier's probability to score

Figure 7.5 presents, for each of the 50 considered situations, the relation between the FSV quantification for player A (the ball carrier which actually shoots in each situation) and the average results of the PE question about what they consider to be the *probability* to score a goal from that specific shot (on a scale from 0 to 10). The linear regression graph of Figure 7.5 suggests a "strong association" between the two variables and shows the sensitivity of the FSV model to capture what might be a shot perceived by coaches as having a greater probability of getting a goal ($R^2 = 0.6706$).

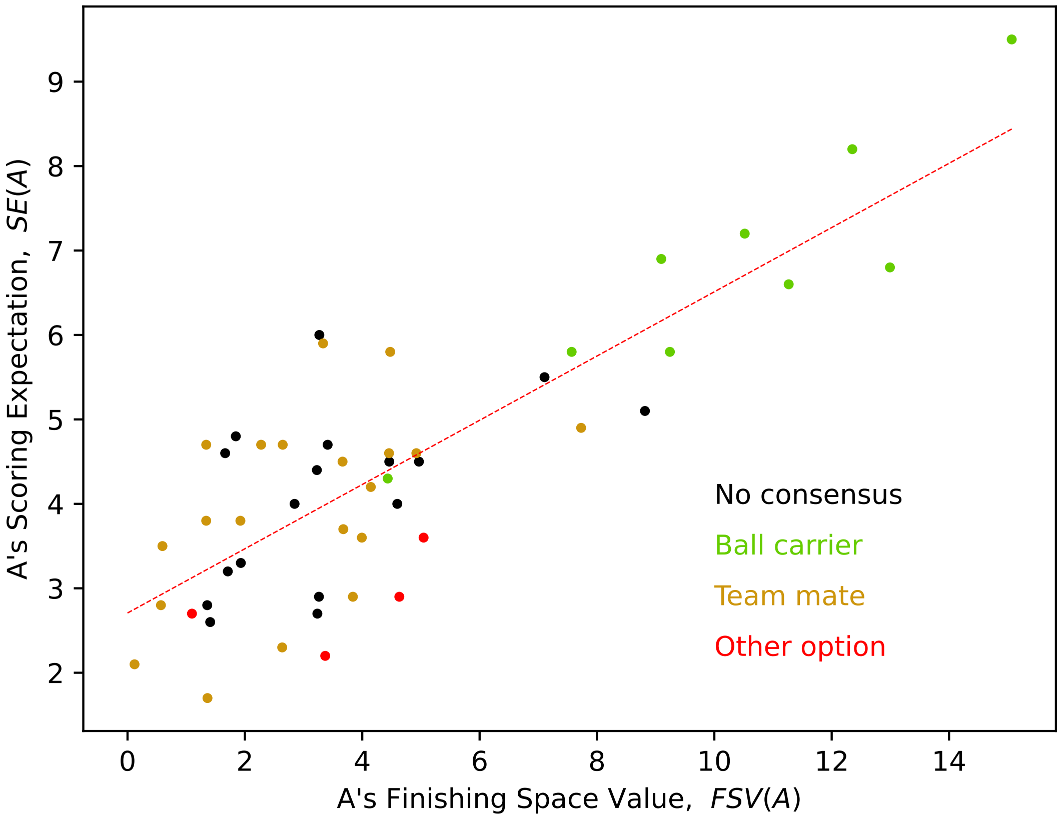



**Figure 7.5:** Linear regression between the result of the FSV and the subjective perception of the Panel of Experts (PE) about the "probability to score from a shoot" of the player's "A" (the ball carrier), in each finishing situation

### 7.3.2 The coaches' "Panel of Experts" (PE) opinion

The number of coaches that choose each option in each situation is presented in Table 7.3 of the Appendix and Figure 7.6 shows the histogram with the frequency of the respective Gwet's agreement coefficient.

The total Gwet's AC1 for this survey was 0.39, demonstrating an agreement among coaches slightly below the "moderate" range (0.40 to 0.60) (Bühn et al., 2021). We must stress that only in 12 situations (24% of the survey), PE's coaches achieve a high agreement (0.80 to 1.00) (Bühn et al., 2021) about what was the "best option" to finish the play. In 18 situations (36% of the survey), the coaches did not express

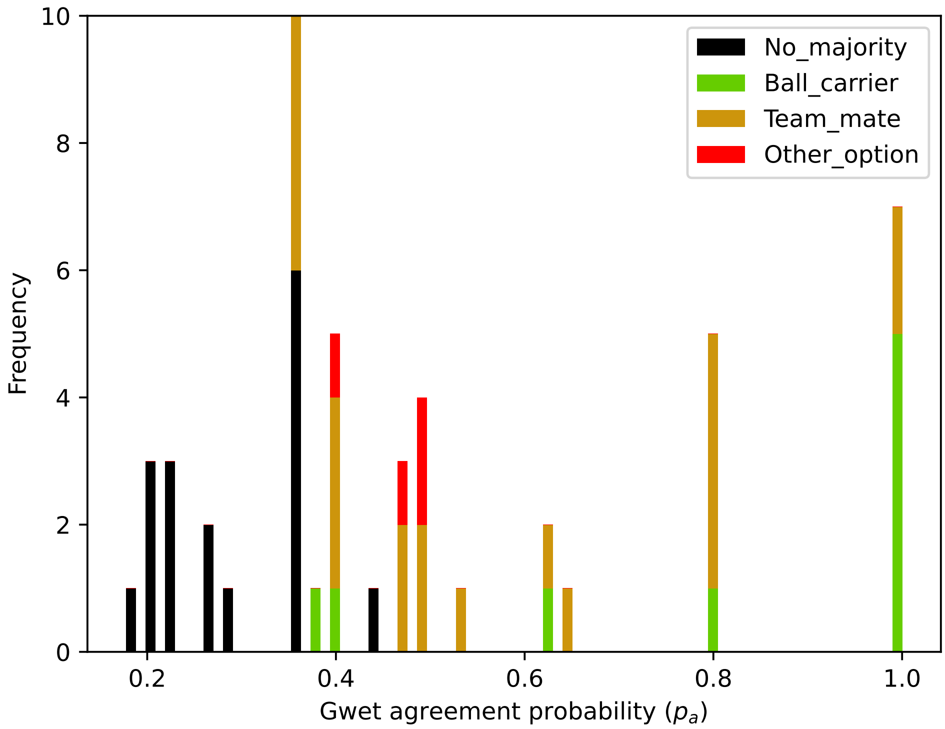



**Figure 7.6:** Histogram with the values of the Gwet's agreement coefficient. It shows the frequency of the situations where the PE did not minimally agree (black, No majority) and the frequency with which the PE produced a tendency in their answers, in the sense that the "best option" to shoot would be: 1) the ball carrier (green, option A); 2) one of his teammates (brown, options B, c or D); 3) Other option (red, E)

.

agreement in any sense. The general "fair agreement" (0.21–0.40) among coaches was contrasted with the probabilistic predictions made by the "Finishing Space Value" (FSV) model. This also indicates that the phenomena itself might be inherently complex, and thus perceived and acted upon in multiple ways.

### 7.3.3 Comparative analysis between the PE and the FSV model

The results of Figure 7.6 show how coaches *differently* perceive the affordances for players in each finishing situation of the match. However, to compare coaches' choice probabilities with the predictions of the "Finishing Space Value" (FSV) model, we used a "multiclass Brier Score" (Figure 7.7).

Figure 7.7, shows how approach I of the FSV model predicted the PE's responses, including the finishing situations where the Gwet's agreement value indicated a low agreement between coaches (see 7.3 and 7.4 of the Appendix). As the Brier Score ranges between 0 (high accuracy) and 1 (low accuracy), the average Brier Score of 0.16 indicates the ability of this the FSV model (approach I) to predict coaches' answers. The lower the score the better.
However, Figure 7.7 also shows the difficulty of the FSV model to adequately predict the coaches' responses when they predominantly choose option A (that the ball carrier should shoot). In fact, Figure 7.7 shows (with green bullets) a set of finishing situations where coaches "highly agreed" (Gwet's = 1.0) that the "best option" to the ball carrier was to shoot but the FSV model (approach I) indicated other players (B,

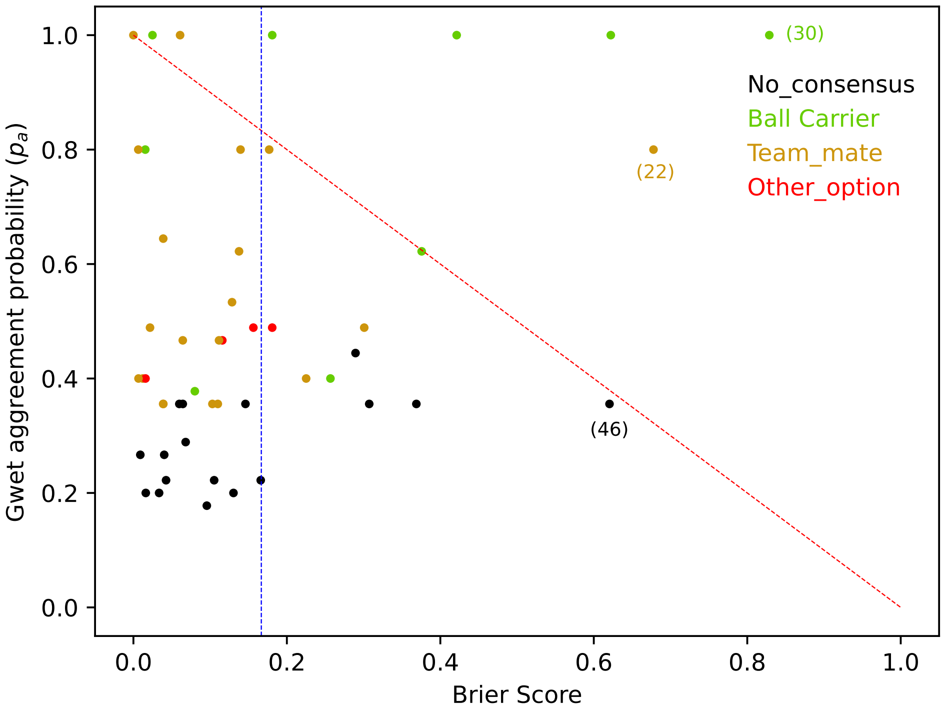



**Figure 7.7:** Graph for each situation of the survey, according to Gwet's agreement probability and the "multiclass Brier Score" for the FSV model (approach I). The vertical blue line indicates a random reference's Brier Score.

C or D passing options), with higher values, as *even* better options.

Thus, we tested the FSV model (approach II), where the option for a shot by the ball carrier was selected whenever its absolute value was higher than a carefully computed threshold (defined in Figure 7.21 of the Appendix) *or* when it was higher than that of the other options (B, C, D or E). With this approach II, the average BS of the FSV model improves to 0.11 increasing the model accuracy to predict coaches' choices regardless of their Gwet's agreement probability (Figure 7.8). This result means that this FSV model, approach II, was 33% better than the blue line of Figure 8 7.8 (the random BS reference).

Is important to note how two finishing situations (22 and 46 in Figure 7.8, with results in Tables 7.3 and 7.4) still have a very poor BS, largely above the blue line that indicates the random "Brier Score reference". These situations indicate the inability of the FSV model (approach II) to correctly predict some coaches' choices.

However, the average Brier Scores of the FSV model (approach I = 0.16 and approach II = 0.11), are more accurate to predict coaches' opinions than models only based on players' locations, i.e., only considering the distance and angle to the goal. In fact, when we considered only the "Player Location" (PL) component of the FSV model, the Brier Score increased to an average of 0.22 (the lower the better) (Table 7.5 and in Figure 7.22 of the Appendix). Very similar results can be observed with the models presented by Pollard and colleagues or by the "Zone" component of Link and colleagues (with an average Brier Score of, respectively, 0.23 and 0.22, as exposed in Table 7.6 and in Figures 7.23 and 7.24 of the Appendix).

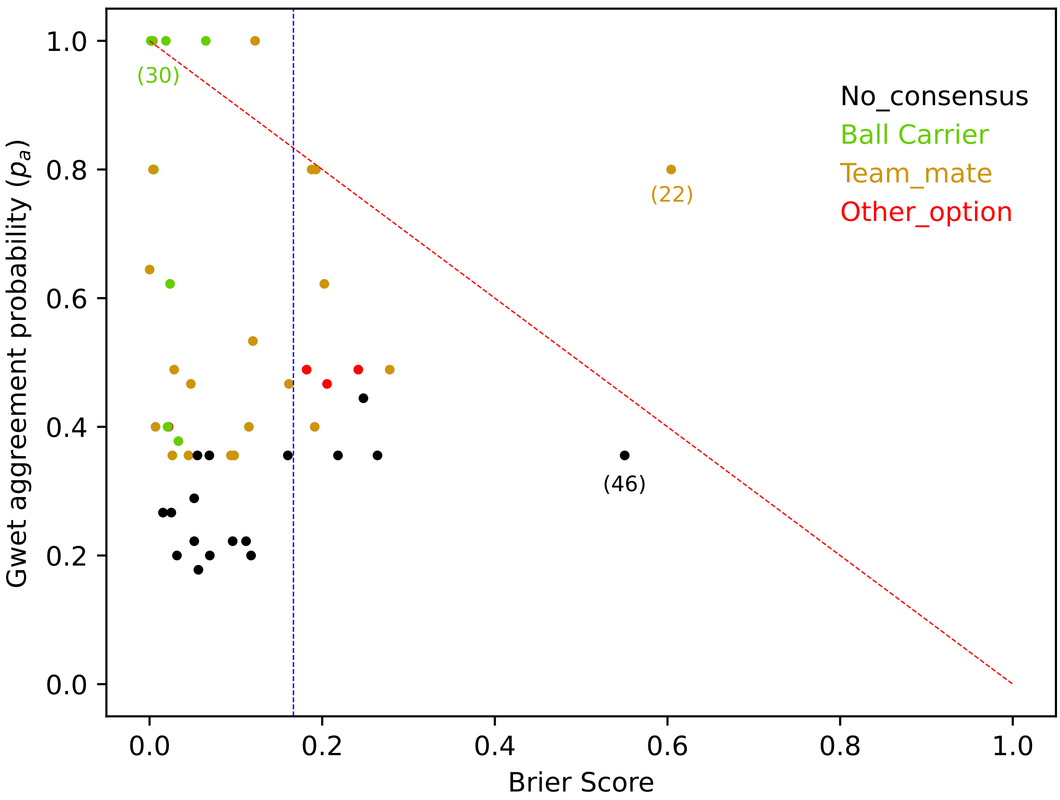



**Figure 7.8:** Graph with each finishing situation according to the values of Gwet's agreement probability and the "multiclass Brier Score" of the FSV model (approach II). The vertical blue line indicates a Brier Score random reference

.

## 7.4 Discussion

In the present study, we investigated football players' decision-making in finishing situations. We hypothesized players' decision-making behaviour is based on their perception of the affordances offered by the match (Fajen, Riley, and Michael T. Turvey, 2009; D. Araújo and K. Davids, 2016). Inspired by the "Expected Possession Value" model (Daniel Cervone et al., 2016; Fernández, Luke Bornn, and Dan Cervone, 2019; Fernández, Luke Bornn, and Daniel Cervone, 2021) we build the "Finishing Space Value" (FSV), which captures the affordance of shot-on-goal-ability in finishing situations.

The novelty of our study is the simplicity of the parameters that constitute the FSV model. We also used an updated new methodology to validate it. The FSV parameters assess how players perceive the affordances created by information from: a) the distance and angle between each player and the opponent's goal; and b) the distance between each player and the nearest opponents.

This model is completely distinct from those denominated as expected goals (xG) models (Eggels, 2016; Rathke, 2017; Spearman, 2018; Pardo, 2020; Rowlinson, 2020; Anzer and Bauer, 2021; Cavus and Biecek, 2022). In fact, even if the parameters and computation of each xG model are diverse, the general idea behind it, is that the shots' success ratio provide the "probability" to score from a given location. To test the plausibility of the FSV model, we applied it to finishing situations, and then ask a panel of expert (PE) football coaches their opinion about a sample of those finishing situations. Results showed that the

FSV model incorporates information from the affordances for players perceived by the PE (Gibson, 1979). Importantly, the PE and the FSV model are highly correlated in their ability to predict when a shot will score ($R^2 = 0.6706$). However, in most of the finishing situations presented to the PE, there was no unanimity in the answers of the coaches. This is demonstrated by a general agreement between coaches that results in a Gwet's AC1 of only 0,39. This indicates that finishing situations as a whole are inherently complex, and thus perceived and acted upon in multiple ways. Coaches perceive the affordances for athletes in multiple ways, maybe as diverse as how athletes perceive the affordances to shooting themselves. Affordances are perceived according to the skills and characteristics of an athlete as well as according to the specificity of the task (D. Araujo, M. Dicks, and K. Davids, 2019). So, if the phenomenon is well captured by the FSV model, it should also express such diversity of how the phenomenon can be perceived and acted upon. Importantly, the results of the multiclass Brier Score (BS) that measured the accuracy of the probabilistic predictions made by the FSV model achieve a value of 0.16. This result of the approach I express was based on the simple comparison among each option of the FSV (see Figures 7.7 and 7.19). Nevertheless, in this approach, it was demonstrated (see for example, the situation (30) in Figure 7.7) that football coaches considered that when the ball carrier is "sufficiently" well located and with enough space to score, he should shoot (Hughes, 1990), even when there are other teammates in a slight better contextual position (as the FSV model captured). With BS approach II, it was assumed that the FSV model will always choose option A (the ball carrier should shoot) when its value is bigger than a threshold (given by the data expressed in Figure 7.21). Interestingly, for this second approach, the BS achieve a value of 0.11 (Figure 7.8), demonstrating how coaches can be sensitive to that kind of perceived thresholds that differentiate the ball carrier from all other teammates (Queiroz, 1986; J. F. Gréhaigne, Bouthier, and David, 1997; Garganta and J. F. Gréhaigne, 1999).

Finally, we did a comparison of the BS achieved by the FSV model in the two computational approaches (0.16 and 0.11), with the situation where only the component "Player Location" was considered (see Figure 7.22. In this case, the BS was worst (0.22) and very similar to the one obtained when we applied the functions proposed by Pollard and colleagues (Pollard, Ensum, and Taylor, 2004) (see Figure 7.23) or the one originated by the "Zone" component of the model proposed by Link and colleagues (Link, Lang, and Seidenschwarz, 2016) (see Figure 7.24). These results demonstrated how the contextual information, about the "free space" around each player, contributes to increasing the accuracy of the model and is relevant for the understanding of dynamic ecologically situated decision-making behaviour in finishing situations in football.

In conclusion, the FSV model (approach II) is able to capture how decision-making behaviour is based on the players' perception of match affordances to shot in finishing situations, as it happens with the decision-making of coaches which is based on their perception of match affordances for players to shot on goal (Duarte Araújo, Brito, and Carrilho, 2022). These affordances are collectively perceived, i.e., they are *shared* affordances (Pedro Silva et al., 2013) and thus can be acted upon in multiple ways according to the skills and characteristics of the perceivers.

### 7.4.1 Limitations and future work

Despite the encouraging results of this study, we are aware that the model needs to be further tested with larger and more diverse data from matches. The phenomenon is inherently complex as it was also expressed by the diversity of opinions of expert football coaches about a given situation. The perception of affordances for players expressed by coaches is influenced by their unique paths in football, embedded in their socio-cultural history and forms of life (Rothwell, Keith Davids, and J. Stone, 2018). For example, the "Panel of Experts" of this study, although performing in high-level football worldwide, were all Portuguese (Santos, Jones, and Mesquita, 2013).
Future testing of the FSV model should also include more diverse data (e.g., from different competitions) to be improved. This will also contribute to overcoming the limitations of the use of simple Voronoi diagrams (VD) as a proxy to "free space" around each player (Efthimiou, 2021). However, the substitution of VD by more complex models of "dominant regions" (Taki and J. i. Hasegawa, 2000) that include players' trajectories and speeds, are not an easy path (Rein, Raabe, and D. Memmert, 2017). It implies transdisciplinary research about sport behaviour, needing to join football players and coaches' experiential knowledge with sports scientists, sports psychologists and data scientists (Rothwell, Keith Davids, J. A. Stone, et al., 2020).

### 7.4.2 Practical applications

The FSV model might contribute to several practical applications:

a) For scouting, the quantification of the players' FSV can support recruitment processes. Notably, in high-performance contexts, increasingly supported by data (Christensen, 2009), the FSV can allow to differentiate between "the efficiency of the shooter" from the "difficulty of the shot" (Gudmundsson and Horton, 2017)[p22].

b) For match analysis, identifying (Filetti et al., 2017) the game moments when a given player or team has higher FSV values, can contribute to improve coaches' decisions about the game (L. Bornn, D. Cervone, and J. Fernandez, 2018).

c) For practice, applying FSV to the analysis of performance in *representative* practice tasks might improve to inform how such practice transfers to performance on the match (Matt Dicks, Keith Davids, and Button, 2009). Thus, coaches can design and better manipulate practice task constraints (Headrick et al., 2012).

## Abbreviations:

Brier Score (BS) Effective Playing Space (EPS) Expected Possession Value (EPV) Finishing Space Value (FSV) Panel of Experts (PE) Player Location (PL) Voronoi Area (VA) Voronoi cell (VC) Voronoi Diagram (VD) Expected Goals (xG)


## Acknowledgement

All data was kindly provided by the STATS© company.


## Disclosure statement

The authors declare no conflict of interest.


## Funding

Duarte Araújo was partly funded by the Fundação para a Ciência e Tecnologia (grant number UIDB/00447/2020, awarded to CIPER-Centro Interdisciplinar para o Estudo da Performance Humana (unit 447). Rui J. Lopes was partly supported by the Fundação para a Ciência e Tecnologia, under Grant Number UIDB/50008/2020 attributed to Instituto de Telecomunicações.


## Data availability

Data was obtained from STATS© company and are available from STATS© with their permission.

## Author contributions

Conceptualisation, N.C., R.J.L. and D.A.; Data curation, N.C., R.J.L and D.F.; Formal analysis, N.C. and R.J.L.; Funding acquisition, D.A.; Investigation, N.C., R.J.L. and D.A.; Methodology, N.C., R.J.L. and D.A.; Software, D.F.; Visualisation, N.C., R.J.L. and D.F.; Supervision, R.J.L. and D.A..; Writing—original draft, N.C.; Writing—review and editing, R.J.L. and D.A. All authors have read and agreed to the published version of the manuscript.

## Additional Figures and Tables

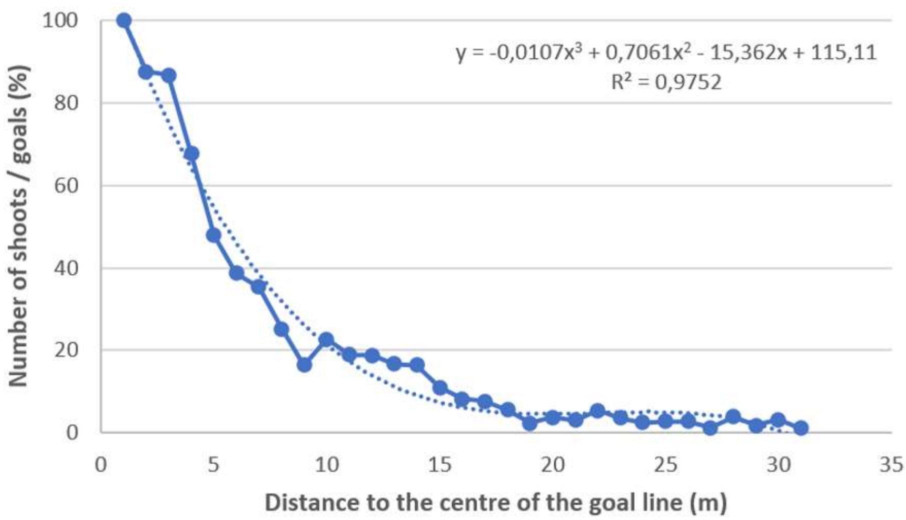



**Figure 7.9:** Player Location and how the distance to the goal influences scoring probability percentage

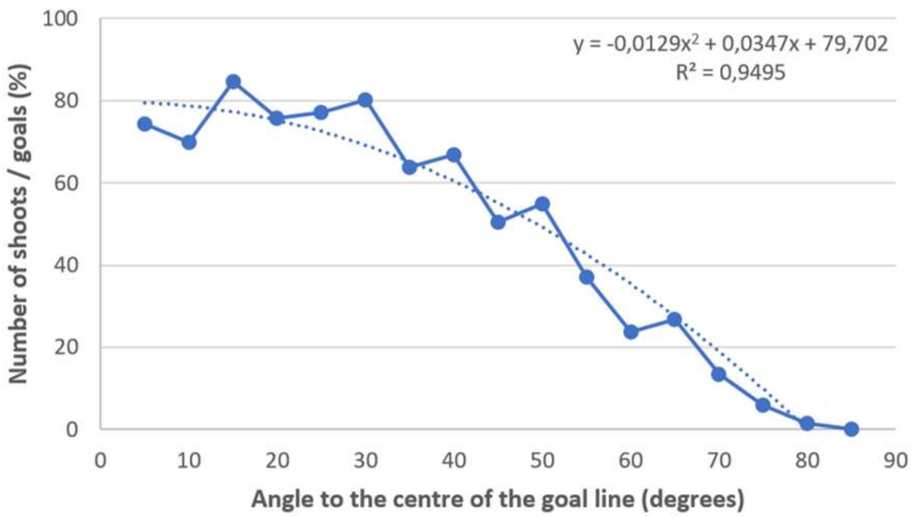
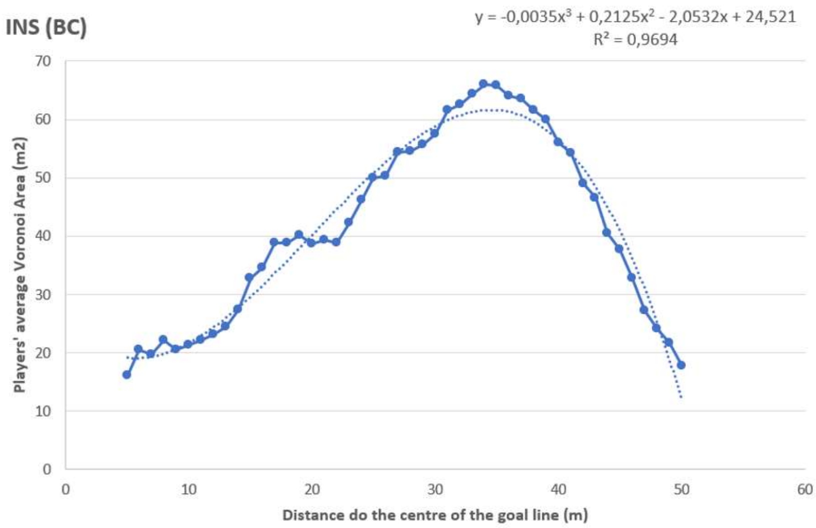
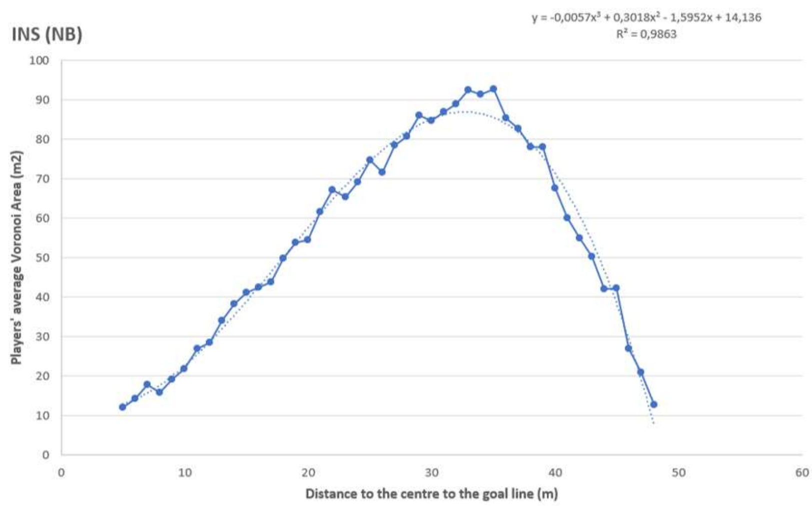



**Figure 7.10:** Player Location and how the angle to the goal influences scoring probability percentage

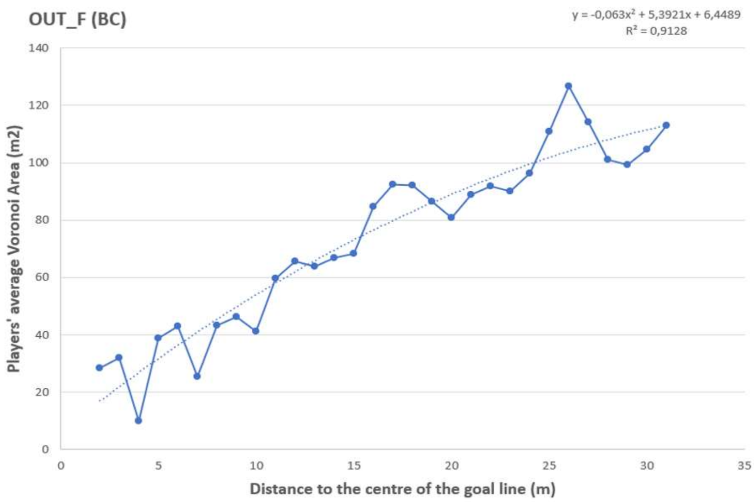



**(a)** Expected Voronoi Area for the ball carrier (BC) INSIDE the EPS

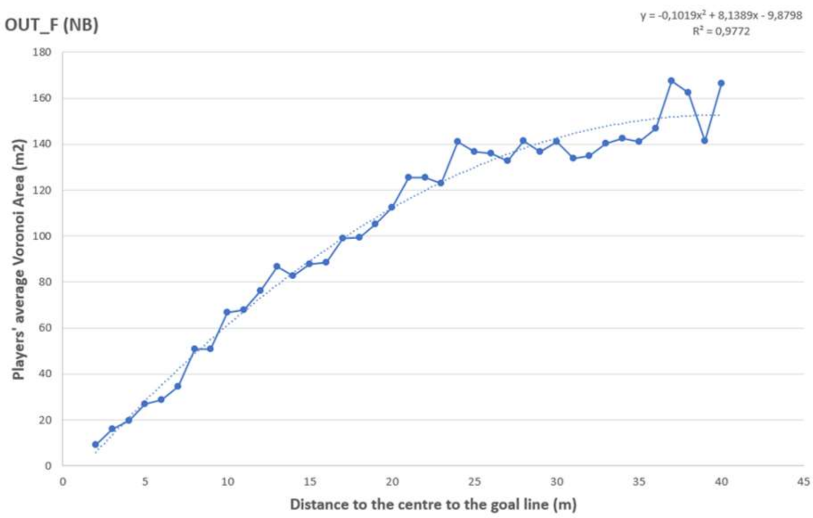



**(b)** Expected Voronoi Area for players without the ball (NB) INSIDE the EPS

**Figure 7.11:** Variation of the average values of the Voronoi areas of players who are with (BC) and without the ball (NB), in the inside zones (INS) of the "Effective Playing Space" (EPS)

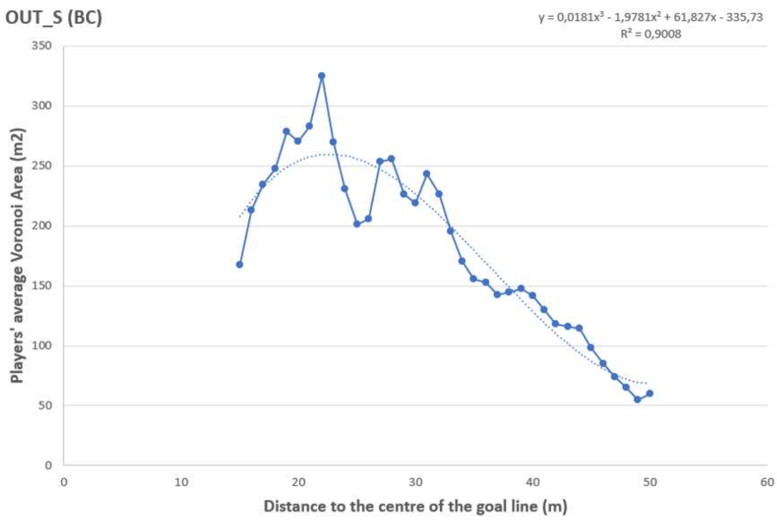



**(a)** Expected Voronoi Area for the ball carrier (BC) Outside Frontal region (OUT_F) of the EPS

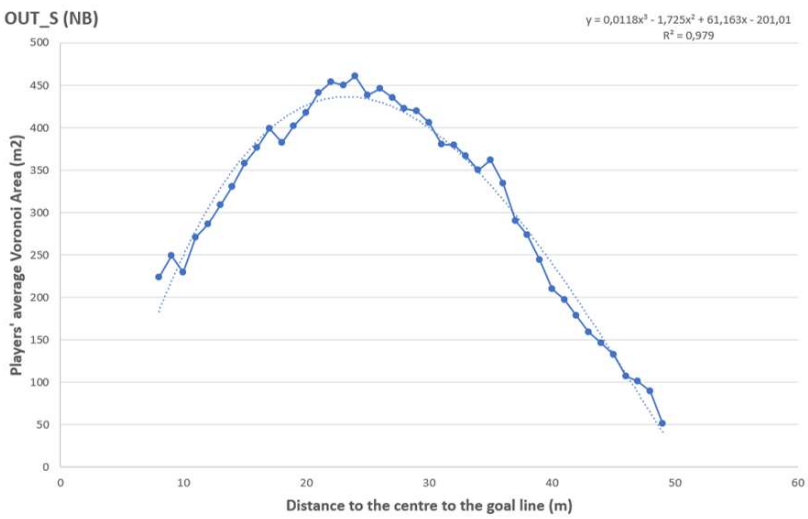



**(b)** Expected Voronoi Area for players without the ball (NB) in the Outside Frontal region (OUT_F) of the EPS

**Figure 7.12:** Variation of the average values of the Voronoi areas of players who are with (BC) and without the ball (NB), in the Outside Frontal regions (OUT_F) of the "Effective Playing Space" (EPS)

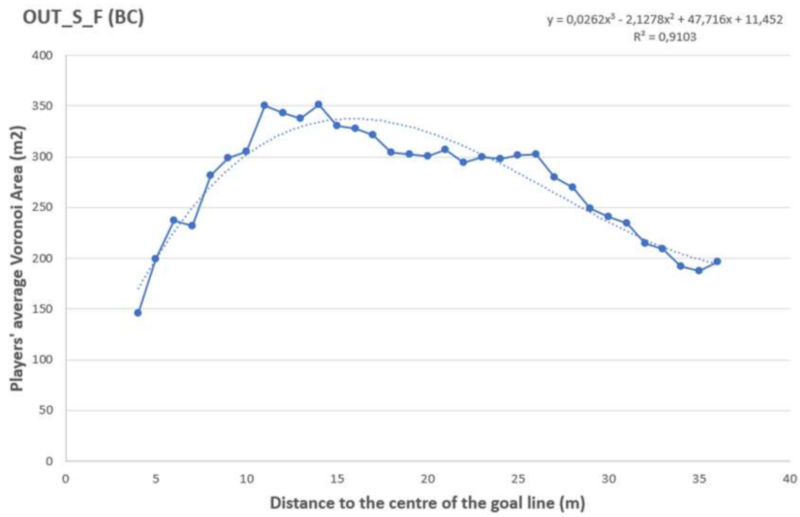



**(a)** Expected Voronoi Area for the ball carrier (BC) Outside Side region (OUT_S) of the EPS

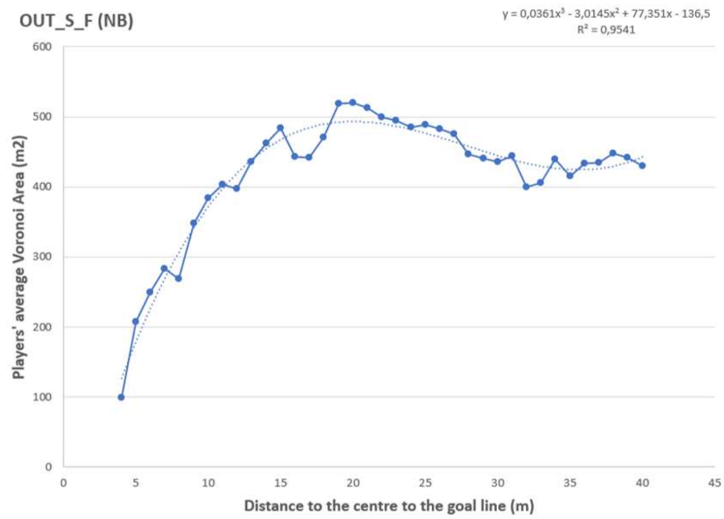



**(b)** Expected Voronoi Area for players without the ball (NB) in the Outside Side region (OUT_S) of the EPS

**Figure 7.13:** Variation of the average values of the Voronoi areas of players who are with (BC) and without the ball (NB), in the Outside Side regions (OUT_S) of the “Effective Playing Space” (EPS)




**(a)** Expected Voronoi Area for the ball carrier (BC) Outside side-frontal region (OUT_S) of the EPS




**(b)** Expected Voronoi Area for players without the ball (NB) in the Outside side-frontal region (OUT_S_F) of the EPS

**Figure 7.14:** Variation of the average values of the Voronoi areas of players who are with (BC) and without the ball (NB), in the Outside Side-Frontal regions (OUT_S_F) of the "Effective Playing Space" (EPS)

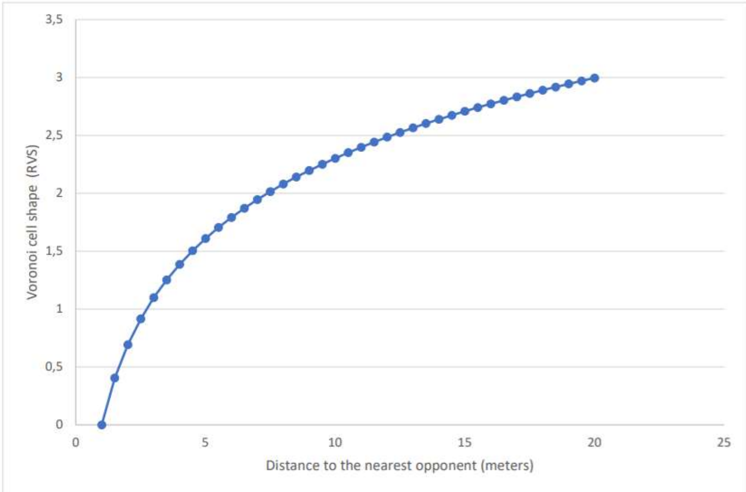



**Figure 7.15:** Graph with the function of the natural logarithm (LN) that is introduced in the FSV model to capture the shape of the Voronoi cell, through the distance to the nearest opponent (DO). [2]

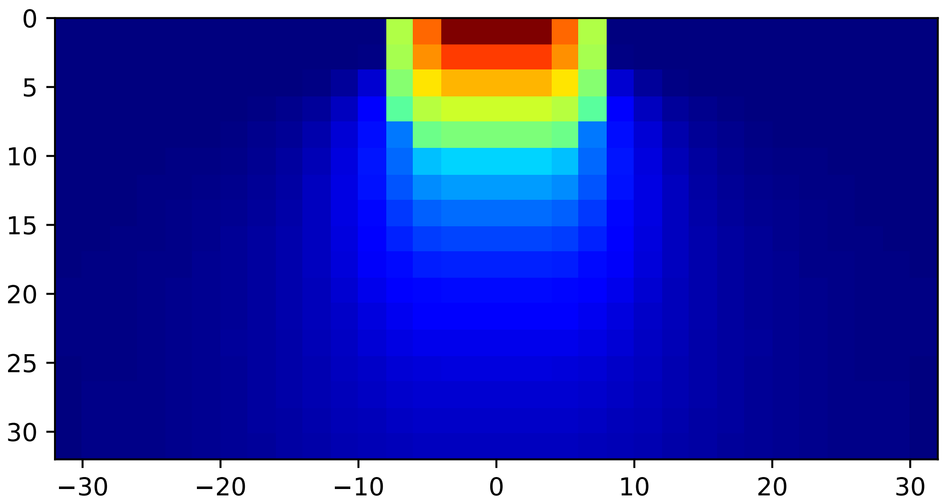



**Figure 7.16:** Heatmap with the probability of scoring calculated by the "Player Location" component of our FSV model (see 7.2.2)

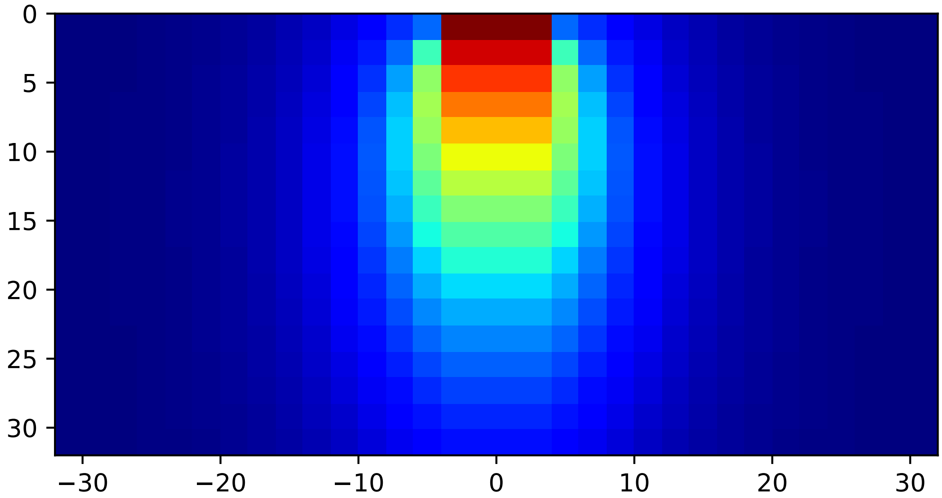



**Figure 7.17:** Heatmap with the probability of scoring calculated by the model of Pollard and colleagues (Pollard, Ensum, and Taylor, 2004)

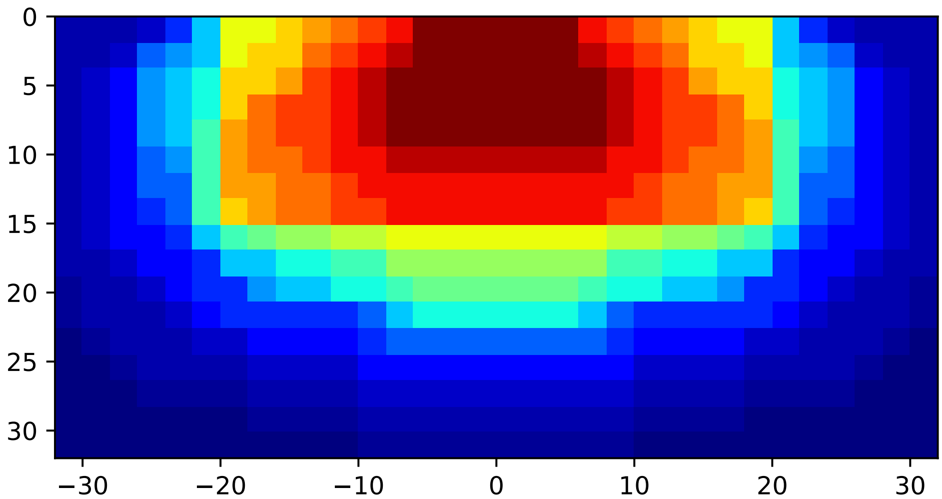



**Figure 7.18:** Heatmap with the probability of scoring calculated by the ”zone” component of the model of Link and colleagues (Link, Lang, and Seidenschwarz, 2016)

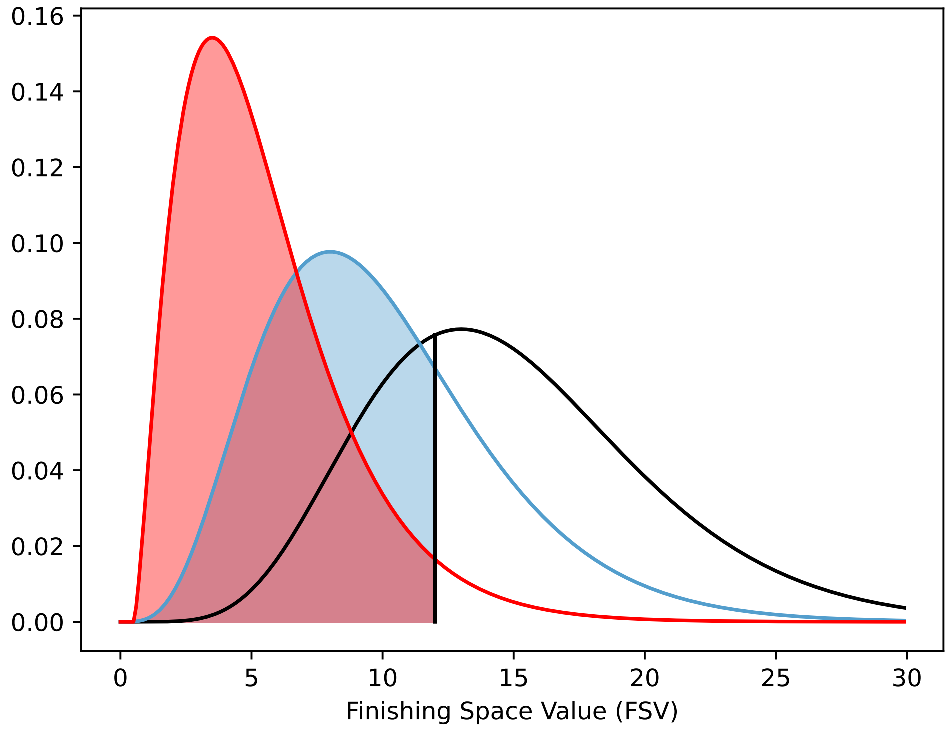



**Figure 7.19:** Exemplary graph of how the FSV of different players was compared. In this case, the probability that player A (black line) has a higher FSV than B (blue line) or C (red line) is given by the respective shaded zones.

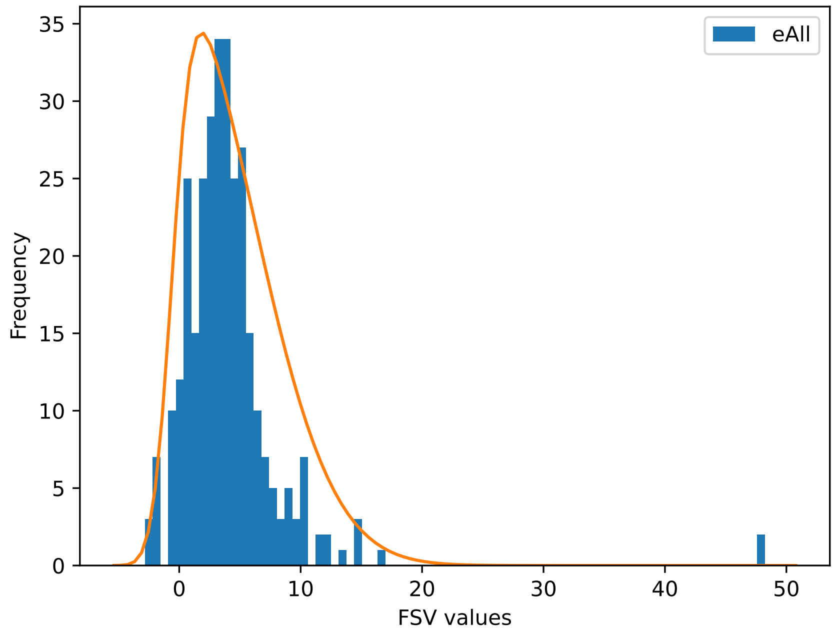



**Figure 7.20:** Histogram with the values of the FSV of each player (A, B, C and D), when each coach chose ”E” as the ”best option” (continue to play, and not shoot or pass to shoot).

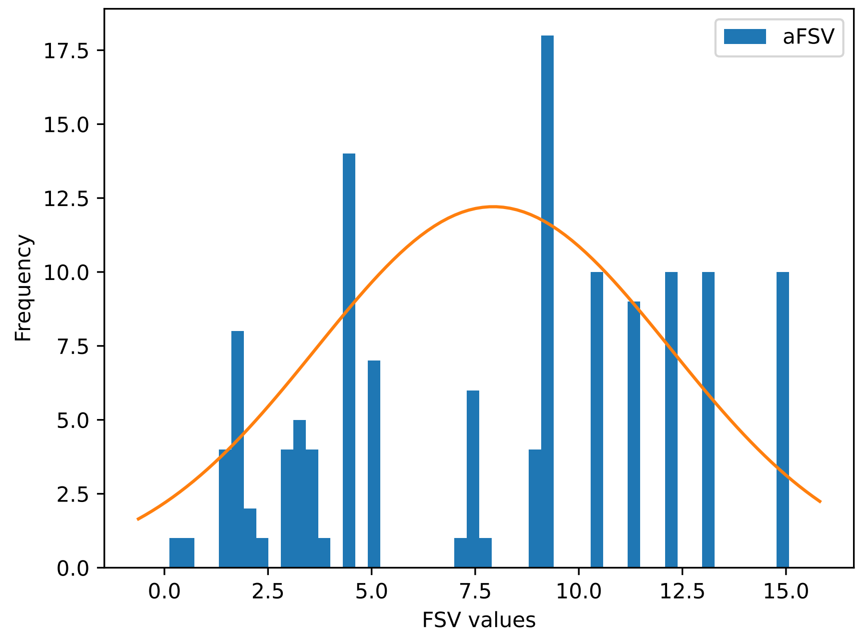



**Figure 7.21:** Histogram with the frequency of the FSV of the ball carrier (player A), when each coach chose him as the ”best option”

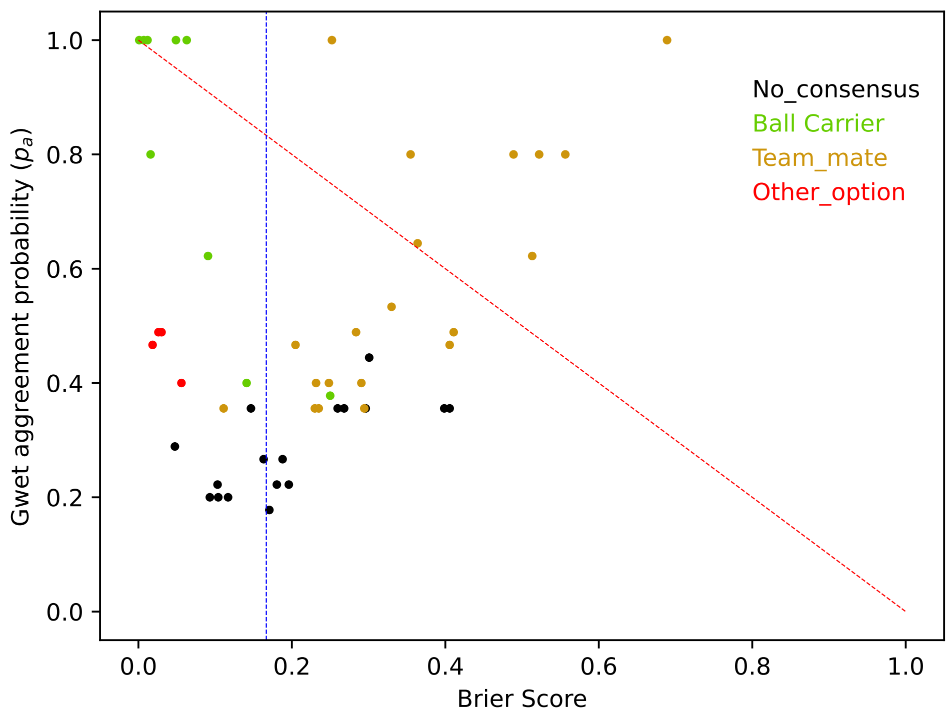



**Figure 7.22:** Graph showing, for each situation of the survey, the comparison between the values of Gwet’s agreement probability and the ”multiclass Brier Score” that measures the accuracy of probabilistic predictions if the FSV model only have the ”Player Location” (distance and angle to the opponnent’s goal). The vertical blue line indicates a Brier Score random reference

.

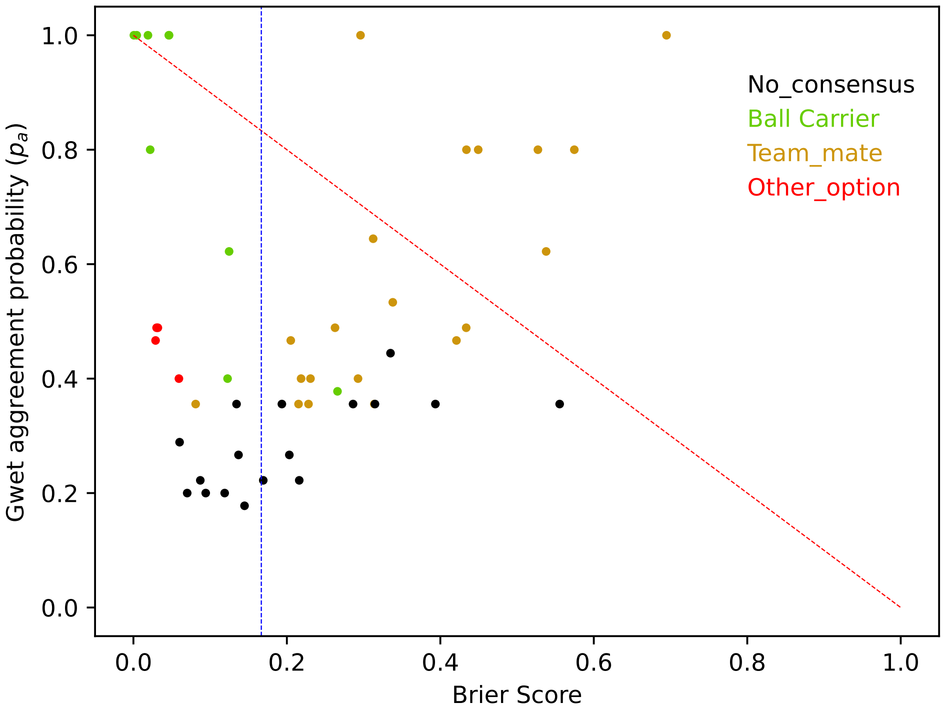



**Figure 7.23:** Graph showing, for each situation of the survey, the comparison between the values of Gwet's agreement probability and the "multiclass Brier Score" that measures the accuracy of probabilistic predictions with model proposed by Pollard and colleagues (Pollard, Ensum, and Taylor, 2004). The vertical blue line indicates a Brier Score random reference

.

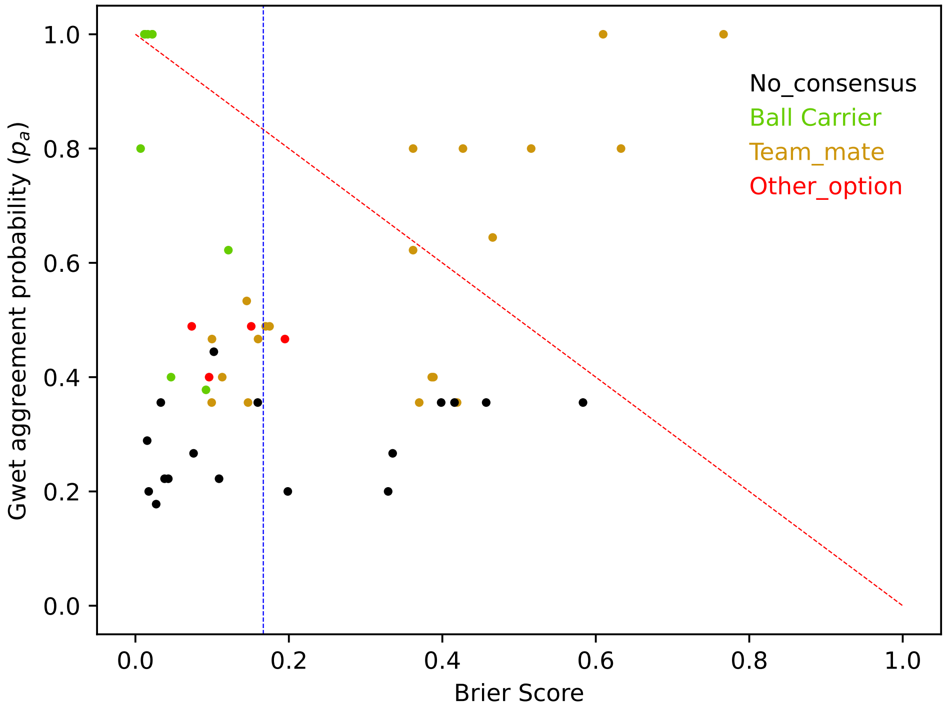



**Figure 7.24:** Graph showing, for each situation of the survey, the comparison between the values of Gwet's agreement probability and the "multiclass Brier Score" that measures the accuracy of probabilistic predictions with the "Zone" component of the "Dangerousity" model proposed by Link and colleagues (Link, Lang, and Seidenschwarz, 2016). The vertical blue line indicates a Brier Score random reference

.

| | PE choices | | | | | | FSV values (A.U.) | | | | Brier Score | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Situation | A | B | C | D | E | **Gwet** | A | B | C | D | Model I | Model II |
| 01 | 4 | 2 | 0 | 1 | 3 | **0.22** | 2.85 | 2.74 | -2.82 | 6.98 | 0.17 | 0.11 |
| 02 | 0 | 3 | 1 | 4 | 2 | **0.22** | 3.26 | 9.07 | 5.07 | 6.41 | 0.04 | 0.05 |
| 03 | 6 | 0 | 0 | 2 | 2 | **0.38** | 4.43 | 3.67 | 0.45 | 2.85 | 0.08 | 0.03 |
| 04 | 10 | 0 | 0 | | 0 | **1.00** | 10.52 | 0,60 | 0,00 | | 0.02 | 0.00 |
| 05 | 2 | 1 | 2 | 4 | 1 | **0.18** | 4.97 | 12.03 | 13.73 | 10.47 | 0.10 | 0.06 |
| 06 | 1 | 6 | 3 | 0 | 0 | **0.40** | 7.73 | 21.08 | 15.74 | 3.24 | 0.01 | 0.12 |
| 07 | 1 | 5 | 0 | 2 | 2 | **0.27** | 4.46 | 14.87 | 4.87 | 9.84 | 0.04 | 0.03 |
| 08 | 3 | 7 | 0 | | 0 | **0.53** | 4.48 | 6.98 | 6.32 | | 0.13 | 0.12 |
| 09 | 0 | 3 | 1 | 0 | 6 | **0.40** | 1.10 | 1.98 | 0.06 | 0.91 | 0.02 | 0.02 |
| 10 | 0 | 2 | 0 | 7 | 1 | **0.49** | 2.64 | 3.15 | 5.45 | 11.40 | 0.02 | 0.03 |
| 11 | 1 | 6 | 2 | 0 | 1 | **0.36** | 3.84 | 9.39 | 0.00 | 5.87 | 0.04 | 0.05 |
| 12 | 1 | 1 | 6 | 0 | 2 | **0.36** | 0.12 | 5.07 | 48.22 | 6.03 | 0.11 | 0.09 |
| 13 | 3 | 1 | 0 | 1 | 5 | **0.29** | 1.84 | 3.95 | 3.29 | 3.60 | 0.07 | 0.05 |
| 14 | 0 | 4 | 5 | 0 | 1 | **0.36** | 3.24 | 4.71 | 10.19 | 3.65 | 0.06 | 0.07 |
| 15 | 4 | 1 | 5 | | 0 | **0.36** | 3.27 | 12.28 | 7.65 | | 0.31 | 0.22 |
| 16 | 2 | 0 | 7 | 0 | 1 | **0.49** | 1.34 | 11.44 | 8.23 | 8.38 | 0.30 | 0.28 |
| 17 | 0 | 9 | 0 | 0 | 1 | **0.80** | 2.64 | 8.73 | 8.22 | 2.25 | 0.18 | 0.19 |
| 18 | 1 | 2 | 6 | 1 | 0 | **0.36** | 1.34 | 5.22 | 15.16 | 8.39 | 0.04 | 0.03 |
| 19 | 0 | 10 | 0 | | 0 | **1.00** | 3.99 | 11.57 | 6.57 | | 0.06 | 0.12 |
| 20 | 0 | 1 | 2 | 0 | 7 | **0.49** | 3.37 | -0.47 | 4.47 | 5.33 | 0.13 | 0.18 |
| 21 | 1 | 0 | 6 | 3 | 0 | **0.40** | 2.28 | 2.65 | 14.30 | 21.81 | 0.23 | 0.19 |
| 22 | 0 | 1 | 9 | 0 | 0 | **0.80** | 3.33 | 23.92 | 9.69 | 13.77 | 0.68 | 0.60 |
| 23 | 0 | 9 | 0 | 0 | 1 | **0.80** | 3.66 | 7.14 | 5.35 | 1.44 | 0.14 | 0.19 |
| 24 | 9 | 0 | 1 | 0 | 0 | **0.80** | 11.27 | -9.60 | 4.65 | 3.08 | 0.02 | 0.01 |
| 25 | 5 | 5 | 0 | 0 | 0 | **0.44** | 1.67 | 2.86 | 4.21 | 1.78 | 0.29 | 0.25 |
| 26 | 4 | 0 | 5 | 0 | 1 | **0.36** | 3.41 | 1.80 | 10.18 | 14.74 | 0.37 | 0.26 |
| 27 | 4 | 0 | 6 | | 0 | **0.47** | 4.92 | 4.56 | 7.45 | | 0.06 | 0.05 |
| 28 | 1 | 1 | 0 | 1 | 7 | **0.47** | 5.05 | 0.46 | 2.45 | 2.36 | 0.12 | 0.21 |
| 29 | 2 | 2 | 0 | 1 | 7 | **0.49** | 4.63 | 3.82 | 5.49 | -1.6 | 0.18 | 0.24 |
| 30 | 10 | 0 | 0 | 0 | 0 | **1.00** | 12.35 | 9.65 | 26.99 | 16.53 | 0.83 | 0.02 |
| 31 | 6 | 0 | 0 | 3 | 1 | **0.40** | 7.57 | 12.27 | 1.86 | 16.57 | 0.26 | 0.02 |
| 32 | 1 | 4 | 1 | 1 | 3 | **0.20** | 3.23 | 7.74 | 6.83 | 3.27 | 0.03 | 0.03 |
| 33 | 0 | 10 | 0 | 0 | 0 | **1.00** | 1.36 | 69.82 | 22.81 | 7.19 | 0.00 | 0.00 |
| 34 | 0 | 0 | 4 | 3 | 3 | **0.27** | 1.71 | 3.37 | 6.36 | 5.03 | 0.01 | 0.02 |
| 35 | 0 | 1 | 5 | 0 | 4 | **0.36** | 1.36 | 3.23 | 10.01 | 3.81 | 0.06 | 0.06 |
| 36 | 1 | 0 | 1 | 6 | 2 | **0.36** | 0.57 | 4.23 | 0.45 | 4.45 | 0.10 | 0.10 |
| 37 | 8 | 0 | 1 | 1 | 0 | **0.62** | 9.24 | 8.46 | 5.72 | 14.77 | 0.38 | 0.02 |
| 38 | 10 | 0 | 0 | 0 | 0 | **1.00** | 9.10 | -7.85 | 11.37 | 8.80 | 0.42 | 0.07 |
| 39 | 2 | 2 | 0 | 4 | 2 | **0.20** | 4.60 | 6.34 | 5.82 | 0.02 | 0.13 | 0.12 |
| 40 | 1 | 4 | 5 | 0 | 0 | **0.36** | 7.10 | 15.72 | 8.50 | 2.54 | 0.15 | 0.16 |
| 41 | 0 | 1 | 6 | 0 | 3 | **0.40** | 0.60 | -0.31 | 6.42 | 0.64 | 0.01 | 0.01 |
| 42 | 4 | 3 | 1 | 1 | 1 | **0.20** | 8.82 | 8.96 | 2.00 | 7.72 | 0.02 | 0.07 |
| 43 | 1 | 4 | 2 | 0 | 3 | **0.22** | 1.41 | 2.00 | 5.61 | 3.97 | 0.11 | 0.10 |
| 44 | 2 | 8 | 0 | 0 | 0 | **0.64** | 4.46 | 31.12 | 9.02 | 1.81 | 0.04 | 0.00 |
| 45 | 10 | 0 | 0 | 0 | 0 | **1.00** | 15.07 | 8.59 | 21.95 | 1.03 | 0.62 | 0.00 |
| 46 | 1 | 5 | 4 | 0 | 0 | **0.36** | 1.93 | 8.84 | 0.00 | 20.52 | 0.62 | 0.55 |
| 47 | 10 | 0 | 0 | 0 | 0 | **1.00** | 12.99 | 3.23 | 10.11 | 10.13 | 0.18 | 0.00 |
| 48 | 0 | 8 | 1 | | 1 | **0.62** | 4.15 | 5.35 | 2.92 | | 0.14 | 0.20 |
| 49 | 1 | 9 | 0 | 0 | 0 | **0.80** | 1.92 | 16.33 | 5.29 | 5.22 | 0.01 | 0.00 |
| 50 | 0 | 0 | 6 | 0 | 0 | **0.47** | 3.68 | 2.11 | 3.53 | 2.51 | 0.11 | 0.16 |
| | | | | **Gwet AC1** | | **0.39** | | | | **Brier Score** | 0.16 | 0.11 |

**Table 7.3:** The table presents the results of the number of coaches that choose each possibility (A,B,C,D or E), in each one of the 50 finishing situations of the survey answered by the ”Panel of Experts” (PE choices). The agreement between the coaches of the PE is calculated by the Gwet's AC1. In the following columns is showed the results of the ”Finishing Space Value” (FSV) for each player in each situation (A, B, C and D). Finally, the last two columns present the Brier Scores that compare the probability of choosing one given “best option” (A, B, C, D or E) in the two approaches: by the subjective answers of a coaches' “panel of experts” (PE) and by the two versions of the Finishing Space Value (FSV) quantification model.

| | Probabilities of FSV model (I) | | | | | | Probabilities of FSV model (II) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Situation | A | B | C | D | E | **BS(I)** | A | B | C | D | E | **BS(II)** |
| 01 | 0.09 | 0.08 | 0.00 | 0.57 | 0.27 | 0.17 | 0.19 | 0.07 | 0.00 | 0.50 | 0.24 | 0.11 |
| 02 | 0.04 | 0.51 | 0.11 | 0.21 | 0.13 | 0.04 | 0.17 | 0.44 | 0.10 | 0.18 | 0.11 | 0.05 |
| 03 | 0.30 | 0.21 | 0.01 | 0.13 | 0.35 | 0.08 | 0.45 | 0.17 | 0.01 | 0.10 | 0.28 | 0.03 |
| 04 | 0.84 | 0.00 | 0.00 | 0.00 | 0.16 | 0.02 | 0.96 | 0.00 | 0.00 | 0.00 | 0.04 | 0.00 |
| 05 | 0.02 | 0.30 | 0.46 | 0.19 | 0.03 | 0.10 | 0.26 | 0.23 | 0.35 | 0.15 | 0.02 | 0.06 |
| 06 | 0.02 | 0.72 | 0.25 | 0.00 | 0.01 | 0.01 | 0.49 | 0.38 | 0.13 | 0.00 | 0.00 | 0.12 |
| 07 | 0.02 | 0.72 | 0.02 | 0.21 | 0.04 | 0.04 | 0.22 | 0.57 | 0.02 | 0.16 | 0.03 | 0.03 |
| 08 | 0.13 | 0.38 | 0.30 | 0.00 | 0.19 | 0.13 | 0.31 | 0.30 | 0.24 | 0.00 | 0.15 | 0.12 |
| 09 | 0.09 | 0.21 | 0.00 | 0.07 | 0.63 | 0.02 | 0.14 | 0.20 | 0.00 | 0.07 | 0.59 | 0.02 |
| 10 | 0.02 | 0.03 | 0.11 | 0.74 | 0.11 | 0.02 | 0.12 | 0.02 | 0.10 | 0.66 | 0.09 | 0.03 |
| 11 | 0.07 | 0.60 | 0.00 | 0.19 | 0.15 | 0.04 | 0.22 | 0.50 | 0.00 | 0.15 | 0.12 | 0.05 |
| 12 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.11 | 0.03 | 0.00 | 0.97 | 0.00 | 0.00 | 0.09 |
| 13 | 0.06 | 0.23 | 0.16 | 0.20 | 0.35 | 0.07 | 0.13 | 0.22 | 0.15 | 0.18 | 0.32 | 0.05 |
| 14 | 0.04 | 0.10 | 0.68 | 0.05 | 0.13 | 0.06 | 0.17 | 0.08 | 0.59 | 0.05 | 0.12 | 0.07 |
| 15 | 0.02 | 0.71 | 0.19 | 0.00 | 0.08 | 0.31 | 0.16 | 0.61 | 0.17 | 0.00 | 0.07 | 0.22 |
| 16 | 0.00 | 0.52 | 0.20 | 0.21 | 0.07 | 0.30 | 0.06 | 0.49 | 0.19 | 0.20 | 0.06 | 0.28 |
| 17 | 0.02 | 0.45 | 0.38 | 0.02 | 0.13 | 0.18 | 0.13 | 0.40 | 0.34 | 0.01 | 0.12 | 0.19 |
| 18 | 0.00 | 0.03 | 0.79 | 0.13 | 0.04 | 0.04 | 0.06 | 0.03 | 0.74 | 0.13 | 0.04 | 0.03 |
| 19 | 0.04 | 0.71 | 0.16 | 0.00 | 0.10 | 0.06 | 0.21 | 0.58 | 0.13 | 0.00 | 0.08 | 0.12 |
| 20 | 0.13 | 0.00 | 0.24 | 0.34 | 0.29 | 0.16 | 0.25 | 0.00 | 0.20 | 0.29 | 0.25 | 0.18 |
| 21 | 0.00 | 0.00 | 0.18 | 0.81 | 0.01 | 0.23 | 0.09 | 0.00 | 0.16 | 0.74 | 0.01 | 0.19 |
| 22 | 0.00 | 0.86 | 0.03 | 0.11 | 0.00 | 0.68 | 0.14 | 0.74 | 0.02 | 0.09 | 0.00 | 0.60 |
| 23 | 0.10 | 0.45 | 0.23 | 0.01 | 0.21 | 0.14 | 0.24 | 0.38 | 0.19 | 0.01 | 0.18 | 0.19 |
| 24 | 0.77 | 0.00 | 0.08 | 0.03 | 0.12 | 0.02 | 0.95 | 0.00 | 0.02 | 0.01 | 0.03 | 0.01 |
| 25 | 0.06 | 0.15 | 0.32 | 0.07 | 0.40 | 0.29 | 0.13 | 0.14 | 0.30 | 0.06 | 0.37 | 0.25 |
| 26 | 0.01 | 0.00 | 0.24 | 0.71 | 0.04 | 0.37 | 0.15 | 0.00 | 0.20 | 0.61 | 0.03 | 0.26 |
| 27 | 0.18 | 0.15 | 0.47 | 0.00 | 0.20 | 0.06 | 0.38 | 0.11 | 0.36 | 0.00 | 0.15 | 0.05 |
| 28 | 0.42 | 0.01 | 0.10 | 0.10 | 0.37 | 0.12 | 0.57 | 0.01 | 0.08 | 0.07 | 0.28 | 0.21 |
| 29 | 0.23 | 0.15 | 0.34 | 0.00 | 0.27 | 0.18 | 0.40 | 0.12 | 0.26 | 0.00 | 0.21 | 0.24 |
| 30 | 0.03 | 0.01 | 0.84 | 0.12 | 0.00 | 0.83 | 0.85 | 0.00 | 0.13 | 0.02 | 0.00 | 0.02 |
| 31 | 0.05 | 0.26 | 0.00 | 0.67 | 0.02 | 0.26 | 0.49 | 0.14 | 0.00 | 0.36 | 0.01 | 0.02 |
| 32 | 0.05 | 0.42 | 0.31 | 0.05 | 0.17 | 0.03 | 0.18 | 0.36 | 0.27 | 0.05 | 0.14 | 0.03 |
| 33 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 0.94 | 0.00 | 0.00 | 0.00 | 0.00 |
| 34 | 0.03 | 0.10 | 0.40 | 0.24 | 0.24 | 0.01 | 0.10 | 0.09 | 0.37 | 0.22 | 0.22 | 0.02 |
| 35 | 0.01 | 0.05 | 0.72 | 0.07 | 0.15 | 0.06 | 0.07 | 0.04 | 0.68 | 0.07 | 0.14 | 0.06 |
| 36 | 0.01 | 0.29 | 0.01 | 0.32 | 0.37 | 0.10 | 0.05 | 0.28 | 0.01 | 0.31 | 0.35 | 0.10 |
| 37 | 0.15 | 0.12 | 0.03 | 0.66 | 0.03 | 0.38 | 0.68 | 0.04 | 0.01 | 0.25 | 0.01 | 0.02 |
| 38 | 0.25 | 0.00 | 0.47 | 0.22 | 0.06 | 0.42 | 0.70 | 0.00 | 0.18 | 0.09 | 0.02 | 0.07 |
| 39 | 0.16 | 0.34 | 0.28 | 0.00 | 0.21 | 0.13 | 0.35 | 0.27 | 0.22 | 0.00 | 0.17 | 0.12 |
| 40 | 0.07 | 0.78 | 0.12 | 0.00 | 0.03 | 0.15 | 0.46 | 0.45 | 0.07 | 0.00 | 0.02 | 0.16 |
| 41 | 0.01 | 0.00 | 0.64 | 0.01 | 0.34 | 0.01 | 0.05 | 0.00 | 0.61 | 0.01 | 0.33 | 0.01 |
| 42 | 0.33 | 0.34 | 0.01 | 0.23 | 0.09 | 0.02 | 0.72 | 0.14 | 0.00 | 0.10 | 0.04 | 0.07 |
| 43 | 0.03 | 0.05 | 0.41 | 0.20 | 0.31 | 0.11 | 0.09 | 0.05 | 0.39 | 0.19 | 0.29 | 0.10 |
| 44 | 0.00 | 0.99 | 0.00 | 0.00 | 0.00 | 0.04 | 0.21 | 0.79 | 0.00 | 0.00 | 0.00 | 0.00 |
| 45 | 0.20 | 0.02 | 0.78 | 0.00 | 0.00 | 0.62 | 0.96 | 0.00 | 0.04 | 0.00 | 0.00 | 0.00 |
| 46 | 0.00 | 0.05 | 0.00 | 0.93 | 0.01 | 0.62 | 0.08 | 0.05 | 0.00 | 0.86 | 0.01 | 0.55 |
| 47 | 0.50 | 0.01 | 0.23 | 0.23 | 0.04 | 0.18 | 0.94 | 0.00 | 0.03 | 0.03 | 0.00 | 0.00 |
| 48 | 0.22 | 0.37 | 0.11 | 0.00 | 0.31 | 0.14 | 0.36 | 0.30 | 0.09 | 0.00 | 0.25 | 0.20 |
| 49 | 0.00 | 0.90 | 0.03 | 0.03 | 0.04 | 0.01 | 0.08 | 0.83 | 0.03 | 0.03 | 0.03 | 0.00 |
| 50 | 0.23 | 0.08 | 0.21 | 0.11 | 0.37 | 0.11 | 0.35 | 0.07 | 0.18 | 0.09 | 0.31 | 0.16 |
| | | | | | **Mean** | **0.16** | | | | | **Mean** | **0.11** |

**Table 7.4:** The table specifies the results of the probabilities of the Finishing Space Value (FSV) quantification model (version I and II) to choose one "best option" in each finishing situation. In each FSV model (I and II), the last column presents the Brier Score (BS), when these probabilities were compared with the probabilities calculated from the coaches' "Panel of Experts" (PE) subjective answers.

| | Probabilities of PL model | | | | | |
|---|---|---|---|---|---|---|
| Situation | A | B | C | D | E | **BS(PL)** |
| 01 | 0.10 | 0.11 | 0.14 | 0.05 | 0.59 | 0.10 |
| 02 | 0.07 | 0.05 | 0.19 | 0.07 | 0.62 | 0.18 |
| 03 | 0.15 | 0.04 | 0.05 | 0.03 | 0.72 | 0.25 |
| 04 | 0.89 | 0.01 | 0.00 | 0.00 | 0.10 | 0.01 |
| 05 | 0.17 | 0.09 | 0.13 | 0.05 | 0.56 | 0.17 |
| 06 | 0.27 | 0.11 | 0.08 | 0.03 | 0.51 | 0.29 |
| 07 | 0.29 | 0.09 | 0.03 | 0.07 | 0.52 | 0.16 |
| 08 | 0.47 | 0.04 | 0.04 | 0.00 | 0.45 | 0.33 |
| 09 | 0.05 | 0.02 | 0.08 | 0.07 | 0.77 | 0.06 |
| 10 | 0.14 | 0.02 | 0.07 | 0.07 | 0.70 | 0.41 |
| 11 | 0.37 | 0.05 | 0.15 | 0.04 | 0.38 | 0.23 |
| 12 | 0.03 | 0.26 | 0.24 | 0.04 | 0.44 | 0.11 |
| 13 | 0.17 | 0.02 | 0.03 | 0.03 | 0.75 | 0.05 |
| 14 | 0.32 | 0.07 | 0.05 | 0.04 | 0.52 | 0.30 |
| 15 | 0.21 | 0.12 | 0.09 | 0.00 | 0.58 | 0.27 |
| 16 | 0.30 | 0.09 | 0.07 | 0.04 | 0.50 | 0.28 |
| 17 | 0.35 | 0.05 | 0.04 | 0.01 | 0.54 | 0.52 |
| 18 | 0.28 | 0.14 | 0.09 | 0.09 | 0.41 | 0.24 |
| 19 | 0.23 | 0.06 | 0.04 | 0.00 | 0.67 | 0.69 |
| 20 | 0.16 | 0.02 | 0.04 | 0.04 | 0.74 | 0.03 |
| 21 | 0.17 | 0.02 | 0.07 | 0.27 | 0.46 | 0.25 |
| 22 | 0.30 | 0.14 | 0.18 | 0.07 | 0.30 | 0.35 |
| 23 | 0.29 | 0.03 | 0.06 | 0.01 | 0.62 | 0.56 |
| 24 | 0.81 | 0.04 | 0.02 | 0.01 | 0.12 | 0.02 |
| 25 | 0.28 | 0.06 | 0.05 | 0.01 | 0.60 | 0.30 |
| 26 | 0.19 | 0.01 | 0.06 | 0.11 | 0.62 | 0.26 |
| 27 | 0.19 | 0.07 | 0.05 | 0.00 | 0.68 | 0.41 |
| 28 | 0.18 | 0.07 | 0.11 | 0.06 | 0.58 | 0.02 |
| 29 | 0.10 | 0.02 | 0.09 | 0.12 | 0.66 | 0.03 |
| 30 | 0.70 | 0.03 | 0.12 | 0.02 | 0.13 | 0.06 |
| 31 | 0.27 | 0.05 | 0.17 | 0.09 | 0.41 | 0.14 |
| 32 | 0.30 | 0.04 | 0.06 | 0.05 | 0.55 | 0.12 |
| 33 | 0.04 | 0.39 | 0.10 | 0.20 | 0.28 | 0.25 |
| 34 | 0.23 | 0.01 | 0.04 | 0.06 | 0.66 | 0.19 |
| 35 | 0.08 | 0.06 | 0.09 | 0.03 | 0.74 | 0.15 |
| 36 | 0.17 | 0.03 | 0.07 | 0.03 | 0.71 | 0.29 |
| 37 | 0.54 | 0.06 | 0.03 | 0.05 | 0.32 | 0.09 |
| 38 | 0.90 | 0.03 | 0.01 | 0.00 | 0.05 | 0.01 |
| 39 | 0.17 | 0.05 | 0.08 | 0.16 | 0.55 | 0.10 |
| 40 | 0.72 | 0.03 | 0.02 | 0.01 | 0.21 | 0.40 |
| 41 | 0.08 | 0.05 | 0.07 | 0.08 | 0.71 | 0.23 |
| 42 | 0.41 | 0.03 | 0.07 | 0.05 | 0.43 | 0.09 |
| 43 | 0.08 | 0.05 | 0.05 | 0.03 | 0.79 | 0.20 |
| 44 | 0.22 | 0.14 | 0.07 | 0.03 | 0.54 | 0.36 |
| 45 | 0.96 | 0.00 | 0.01 | 0.00 | 0.03 | 0.00 |
| 46 | 0.10 | 0.06 | 0.00 | 0.18 | 0.65 | 0.41 |
| 47 | 0.73 | 0.01 | 0.10 | 0.03 | 0.13 | 0.05 |
| 48 | 0.19 | 0.02 | 0.06 | 0.00 | 0.72 | 0.51 |
| 49 | 0.14 | 0.13 | 0.05 | 0.07 | 0.61 | 0.49 |
| 50 | 0.21 | 0.02 | 0.07 | 0.01 | 0.69 | 0.20 |
| | | | | | **Mean** | **0.22** |

**Table 7.5:** The table presents the results of the probabilities of a quantification model that only includes the ”Player Location” (distance and angle to the opponent's goal) to choose one ”best option” in each finishing situation. The last column presents the Brier Score of this model (BS PL), when these probabilities were compared with the probabilities calculated from the coaches' ”Panel of Experts” (PE) subjective answers.

| | Probabilities of the model: Pollard et.al | | | | | | Probabilities of the model: Link et.al. | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Situation | A | B | C | D | E | **BS** | A | B | C | D | E | **BS** |
| 01 | 0.11 | 0.15 | 0.19 | 0.04 | 0.51 | 0.09 | 0.08 | 0.29 | 0.31 | 0.11 | 0.20 | 0.11 |
| 02 | 0.07 | 0.04 | 0.23 | 0.07 | 0.58 | 0.17 | 0.08 | 0.14 | 0.30 | 0.28 | 0.19 | 0.04 |
| 03 | 0.15 | 0.03 | 0.05 | 0.02 | 0.75 | 0.27 | 0.25 | 0.13 | 0.17 | 0.13 | 0.31 | 0.09 |
| 04 | 0.85 | 0.02 | 0.00 | 0.00 | 0.13 | 0.02 | 0.85 | 0.06 | 0.00 | 0.00 | 0.08 | 0.02 |
| 05 | 0.16 | 0.11 | 0.18 | 0.05 | 0.50 | 0.14 | 0.20 | 0.22 | 0.24 | 0.21 | 0.12 | 0.03 |
| 06 | 0.52 | 0.09 | 0.07 | 0.01 | 0.31 | 0.29 | 0.77 | 0.08 | 0.08 | 0.03 | 0.04 | 0.39 |
| 07 | 0.27 | 0.12 | 0.03 | 0.09 | 0.49 | 0.14 | 0.77 | 0.08 | 0.03 | 0.08 | 0.04 | 0.34 |
| 08 | 0.41 | 0.05 | 0.04 | 0.00 | 0.49 | 0.34 | 0.41 | 0.24 | 0.14 | 0.00 | 0.21 | 0.15 |
| 09 | 0.06 | 0.01 | 0.09 | 0.08 | 0.76 | 0.06 | 0.03 | 0.13 | 0.26 | 0.26 | 0.33 | 0.10 |
| 10 | 0.08 | 0.01 | 0.08 | 0.07 | 0.75 | 0.43 | 0.05 | 0.15 | 0.22 | 0.22 | 0.36 | 0.17 |
| 11 | 0.42 | 0.05 | 0.16 | 0.04 | 0.32 | 0.23 | 0.81 | 0.05 | 0.06 | 0.05 | 0.02 | 0.42 |
| 12 | 0.10 | 0.29 | 0.27 | 0.03 | 0.32 | 0.08 | 0.20 | 0.25 | 0.25 | 0.19 | 0.12 | 0.10 |
| 13 | 0.16 | 0.01 | 0.02 | 0.01 | 0.79 | 0.06 | 0.15 | 0.16 | 0.07 | 0.09 | 0.53 | 0.02 |
| 14 | 0.30 | 0.09 | 0.05 | 0.03 | 0.53 | 0.29 | 0.78 | 0.08 | 0.05 | 0.05 | 0.05 | 0.46 |
| 15 | 0.30 | 0.14 | 0.10 | 0.00 | 0.46 | 0.19 | 0.78 | 0.09 | 0.08 | 0.00 | 0.05 | 0.16 |
| 16 | 0.25 | 0.13 | 0.10 | 0.03 | 0.48 | 0.26 | 0.38 | 0.19 | 0.19 | 0.12 | 0.11 | 0.17 |
| 17 | 0.32 | 0.05 | 0.04 | 0.00 | 0.58 | 0.53 | 0.49 | 0.14 | 0.15 | 0.01 | 0.21 | 0.43 |
| 18 | 0.39 | 0.15 | 0.09 | 0.09 | 0.28 | 0.22 | 0.76 | 0.08 | 0.07 | 0.07 | 0.03 | 0.37 |
| 19 | 0.23 | 0.06 | 0.03 | 0.00 | 0.67 | 0.69 | 0.80 | 0.06 | 0.05 | 0.00 | 0.09 | 0.77 |
| 20 | 0.08 | 0.01 | 0.04 | 0.03 | 0.84 | 0.03 | 0.05 | 0.14 | 0.17 | 0.24 | 0.41 | 0.07 |
| 21 | 0.24 | 0.01 | 0.08 | 0.27 | 0.39 | 0.22 | 0.77 | 0.03 | 0.07 | 0.09 | 0.04 | 0.39 |
| 22 | 0.53 | 0.12 | 0.13 | 0.06 | 0.16 | 0.45 | 0.76 | 0.07 | 0.07 | 0.06 | 0.03 | 0.63 |
| 23 | 0.25 | 0.02 | 0.07 | 0.00 | 0.66 | 0.57 | 0.37 | 0.17 | 0.17 | 0.01 | 0.28 | 0.36 |
| 24 | 0.77 | 0.07 | 0.03 | 0.00 | 0.13 | 0.02 | 0.82 | 0.07 | 0.06 | 0.01 | 0.04 | 0.01 |
| 25 | 0.23 | 0.07 | 0.04 | 0.00 | 0.65 | 0.34 | 0.35 | 0.19 | 0.18 | 0.04 | 0.24 | 0.10 |
| 26 | 0.04 | 0.00 | 0.00 | 0.00 | 0.96 | 0.56 | 0.01 | 0.01 | 0.01 | 0.01 | 0.98 | 0.58 |
| 27 | 0.17 | 0.08 | 0.05 | 0.00 | 0.69 | 0.42 | 0.25 | 0.23 | 0.21 | 0.00 | 0.31 | 0.16 |
| 28 | 0.17 | 0.09 | 0.15 | 0.05 | 0.54 | 0.03 | 0.22 | 0.25 | 0.25 | 0.13 | 0.16 | 0.19 |
| 29 | 0.09 | 0.01 | 0.11 | 0.16 | 0.63 | 0.03 | 0.04 | 0.12 | 0.23 | 0.34 | 0.27 | 0.15 |
| 30 | 0.74 | 0.04 | 0.11 | 0.02 | 0.09 | 0.05 | 0.86 | 0.05 | 0.05 | 0.03 | 0.02 | 0.01 |
| 31 | 0.28 | 0.05 | 0.20 | 0.12 | 0.35 | 0.12 | 0.77 | 0.05 | 0.08 | 0.07 | 0.04 | 0.05 |
| 32 | 0.29 | 0.03 | 0.06 | 0.06 | 0.56 | 0.12 | 0.78 | 0.03 | 0.05 | 0.09 | 0.05 | 0.33 |
| 33 | 0.17 | 0.32 | 0.11 | 0.22 | 0.19 | 0.30 | 0.63 | 0.11 | 0.10 | 0.11 | 0.04 | 0.61 |
| 34 | 0.20 | 0.00 | 0.03 | 0.06 | 0.71 | 0.20 | 0.27 | 0.03 | 0.15 | 0.19 | 0.37 | 0.08 |
| 35 | 0.09 | 0.05 | 0.11 | 0.02 | 0.73 | 0.13 | 0.09 | 0.17 | 0.34 | 0.12 | 0.28 | 0.03 |
| 36 | 0.16 | 0.01 | 0.08 | 0.02 | 0.74 | 0.31 | 0.26 | 0.07 | 0.24 | 0.12 | 0.32 | 0.15 |
| 37 | 0.46 | 0.09 | 0.03 | 0.08 | 0.34 | 0.12 | 0.37 | 0.20 | 0.13 | 0.19 | 0.11 | 0.12 |
| 38 | 0.92 | 0.03 | 0.01 | 0.01 | 0.04 | 0.00 | 0.81 | 0.06 | 0.05 | 0.05 | 0.02 | 0.02 |
| 39 | 0.19 | 0.04 | 0.08 | 0.22 | 0.47 | 0.07 | 0.71 | 0.06 | 0.07 | 0.10 | 0.06 | 0.20 |
| 40 | 0.73 | 0.04 | 0.02 | 0.00 | 0.20 | 0.39 | 0.83 | 0.06 | 0.06 | 0.01 | 0.04 | 0.42 |
| 41 | 0.09 | 0.05 | 0.07 | 0.10 | 0.70 | 0.23 | 0.07 | 0.16 | 0.21 | 0.25 | 0.32 | 0.11 |
| 42 | 0.36 | 0.03 | 0.11 | 0.05 | 0.44 | 0.09 | 0.37 | 0.16 | 0.18 | 0.18 | 0.10 | 0.02 |
| 43 | 0.09 | 0.04 | 0.04 | 0.01 | 0.82 | 0.22 | 0.11 | 0.17 | 0.22 | 0.06 | 0.44 | 0.04 |
| 44 | 0.48 | 0.14 | 0.05 | 0.01 | 0.32 | 0.31 | 0.83 | 0.07 | 0.04 | 0.02 | 0.04 | 0.47 |
| 45 | 0.97 | 0.00 | 0.01 | 0.00 | 0.02 | 0.00 | 0.87 | 0.04 | 0.05 | 0.02 | 0.02 | 0.01 |
| 46 | 0.27 | 0.07 | 0.00 | 0.19 | 0.47 | 0.31 | 0.78 | 0.09 | 0.00 | 0.09 | 0.05 | 0.40 |
| 47 | 0.74 | 0.01 | 0.10 | 0.05 | 0.11 | 0.05 | 0.81 | 0.04 | 0.06 | 0.06 | 0.02 | 0.02 |
| 48 | 0.17 | 0.01 | 0.06 | 0.00 | 0.75 | 0.54 | 0.28 | 0.08 | 0.21 | 0.00 | 0.43 | 0.36 |
| 49 | 0.18 | 0.16 | 0.04 | 0.07 | 0.55 | 0.43 | 0.72 | 0.10 | 0.05 | 0.07 | 0.06 | 0.52 |
| 50 | 0.19 | 0.01 | 0.08 | 0.00 | 0.72 | 0.21 | 0.26 | 0.07 | 0.25 | 0.05 | 0.36 | 0.10 |
| | | | **Mean (Pollard et.al.)** | | | **0.23** | | | | **Mean (Link et. al.)** | | **0.22** |

**Table 7.6:** The table specifies the results of the probabilities of the quantification models already presented by Pollard and colleagues (Pollard, Ensum, and Taylor, 2004) and Link and colleagues (Link, Lang, and Seidenschwarz, 2016) (in this case, only to its component "Zone"). The last column of each model presents the Brier Score (BS), when these probabilities were compared with the probabilities calculated from the coaches' "Panel of Experts" (PE) subjective answers.

## References


Aguilera, Miguel and Manuel Heras-escribano (2019). "Quantifying affordances through information theory". In: *Artificial Life Conference Proceedings*. One Rogers Street, Cambridge, pp. 32–39.

Amon, Mary Jean, Hana Vrzakova, and Sidney K. D'Mello (2019). "Beyond Dyadic Coordination: Multimodal Behavioral Irregularity in Triads Predicts Facets of Collaborative Problem Solving". In: *Cognitive Science* 43.10, pp. 1–22. DOI: 10.1111/cogs.12787.

Anzer, Gabriel and Pascal Bauer (2021). "A Goal Scoring Probability Model for Shots Based on Synchronized Positional and Event Data in Football (Soccer)". In: *Frontiers in Sports and Active Living* 3.March, pp. 1–15. DOI: 10.3389/fspor.2021.624475.

Araujo, D., M. Dicks, and K. Davids (2019). "Selecting among Affordances: A Basis for Channeling Expertise in Sport". In: *Handbook of embodied cognition and sport psychology*. MIT Press, pp. 557–580. ISBN: 9780262038508.

Araujo, Duarte and Ian Renshaw (2010). "The concept of ' Organismic Asymmetry ' in sport science". In: *Journal of Science and Medicine in Sport* 13, pp. 633–640. DOI: 10.1016/j.jsams.2010.05.002.

Araujo, J et al. (2019). "Ecological cognition : expert decision-making behaviour in sport". In: *International Review of Sport and Exercise Psychology* 12.1, pp. 1–25. URL: http://shura.shu.ac.uk/16154/.

Araújo, D. and K. Davids (2016). "Team synergies in sport: Theory and measures". In: *Frontiers in Psychology* 7.SEP, pp. 1–13. DOI: 10.3389/fpsyg.2016.01449Team.

Araújo, D., P. Silva, and J. Ramos (2014). "Affordance-based decisions guide team synergies during match performance". In: *Research in Physical Education, Sport and Health* 3.1, pp. 19–26.

Araújo, Duarte, Henrique Brito, and Daniel Carrilho (2022). "Team decision-making behavior: An ecological dynamics approach". In: *Asian Journal of Sport and Exercise Psychology* July. DOI: 10.1016/j.ajsep.2022.09.005.

Araújo, Duarte and Keith Davids (2011). "What exactly is acquired during skill acquisition?" In: *Journal of Consciousness Studies* 18.3-4, pp. 7–23.

Araújo, Duarte, Keith Davids, and Robert Hristovski (2006). "The ecological dynamics of decision making in sport". In: *Psychology of Sport and Exercise* 7.6, pp. 653–676. DOI: 10.1016/j.psychsport.2006.07.002.

Araújo, Duarte, João Ramos, and Rui Lopes (2016). "Shared affordances guide interpersonal synergies in sport teams". In: *Interpersonal coordination and performance in social systems*. Routledge, pp. 183–196.

Baysal, Sermetcan and Pinar Duygulu (2016). "Sentioscope: A Soccer Player Tracking System Using Model Field Particles". In: *IEEE Transactions on Circuits and Systems for Video Technology* 26.7, pp. 1350–1362. DOI: 10.1109/TCSVT.2015.2455713.

Bornn, L., D. Cervone, and J. Fernandez (2018). "Soccer analytics: Unravelling the complexity of "the beautiful game"". In: *Significance* 15(3).3, pp. 26–29.

Bühn, Stefanie et al. (2021). "Measuring test-retest reliability (TRR) of AMSTAR provides moderate to perfect agreement - a contribution to the discussion of the importance of TRR in relation to the psychometric properties of assessment tools”. In: *BMC Medical Research Methodology* 21.1, pp. 1–7. ISSN: 14712288. DOI: 10.1186/s12874-021-01231-y.

Button, Chris et al. (2013). “A nonlinear pedagogy for sports teams as social neurobiological systems: how teams can harness self-organization tendencies”. In: *Complexity thinking in physical education*. Routledge, pp. 161–176.

Caetano, Fabio Giuliano et al. (2021). “Football player dominant region determined by a novel model based on instantaneous kinematics variables”. In: *Scientific Reports* 11.1, pp. 1–10. ISSN: 2045-2322. DOI: 10.1038/s41598-021-97537-4. URL: https://doi.org/10.1038/s41598-021-97537-4.

Cavus, Mustafa and Przemysław Biecek (2022). “Explainable expected goal models for performance”. In: *arXiv preprint arXiv:2206.07212.* arXiv: arXiv:2206.07212v2.

Cervone, Daniel et al. (2016). “A Multiresolution Stochastic Process Model for Predicting Basketball Possession Outcomes”. In: *Journal of the American Statistical Association* 111.514, pp. 585–599. DOI: 10.1080/01621459.2016.1141685. arXiv: 1408.0777.

Chiu, S. N. (2003). “Spatial point pattern analysis by using Voronoi diagrams and Delaunay tessellations - A comparative study”. In: *Biometrical Journal* 45.3, pp. 367–376. DOI: 10.1002/bimj.200390018.

Christensen, Mette (2009). “”An Eye for Talent”: Talent Identification and the ”Practical Sense” of Top-Level Soccer Coaches”. In: *Sociology of Sport Journal* 26, pp. 365–382.

Di Salvo, Valter et al. (2006). “Validation of Prozone ®: A new video-based performance analysis system”. In: *International Journal of Performance Analysis in Sport* 6.1, pp. 108–119. DOI: 10.1080/24748668.2006.11868359.

Dicks, Matt, Keith Davids, and Chris Button (2009). “Representative task designs for the study of perception and action in sport”. In: *International Journal of Sport Psychology* 40.4, pp. 506–524.

Duarte, Ricardo et al. (2010). “A Emergência da Tomada de Decisão no Futebol: da Decisão Individual para a Colectiva”. In: *Actas do VII Simpósio Nacional de Investigação em Psicologia*, pp. 1829–1839.

Efthimiou, Costas J. (2021). “The Voronoi Diagram in Soccer: a theoretical study to measure dominance space”. In: *arXiv preprint arXiv:2107.05714.*, pp. 1–32. arXiv: 2107.05714.

Eggels, H. (2016). “Expected Goals in Soccer: Explaining Match Results using Predictive Analytics”. PhD thesis.

Fajen, Brett R., Michael A. Riley, and Michael T. Turvey (2009). “Information, affordances, and the control of action in sport”. In: *International Journal of Sport Psychology* 40.1, pp. 79–107.

Fernández, Javier, Luke Bornn, and Dan Cervone (2019). “Decomposing the Immeasurable Sport: A deep learning expected possession value framework for soccer”. In: *MIT Sloan Sports Analytics Conference*, pp. 1–18.

Fernández, Javier, Luke Bornn, and Daniel Cervone (2021). *A framework for the fine - grained evaluation of the instantaneous expected value of soccer possessions*. Vol. 110. 6. Springer US, pp. 1389–1427. ISBN: 0123456789. DOI: 10.1007/s10994-021-05989-6. URL: https://doi.org/10.1007/s10994-021-05989-6.

Ferreira, A. (2013). “From game momentum to criticality of game situations”. In: *Routledge handbook of sports performance analysis*. Routledge, pp. 270–282.

Filetti, Cristoforo et al. (2017). “A Study of Relationships among Technical, Tactical, Physical Parameters and Final Outcomes in Elite Soccer Matches as Analyzed by a Semiautomatic Video Tracking System”. In: *Perceptual and Motor Skills* 124.3, pp. 601–620. DOI: 10.1177/0031512517692904.

Fonseca, Sofia et al. (2012). “Spatial dynamics of team sports exposed by Voronoi diagrams”. In: *Human Movement Science* 31.6, pp. 1652–1659. DOI: 10.1016/j.humov.2012.04.006.

Franchak, John and Karen Adolph (2014). “Affordances as Probabilistic Functions: Implications for Development, Perception, and Decisions for Action”. In: *Ecological Psychology* 26.1-2, pp. 109–124. DOI: 10.1080/10407413.2014.874923.Affordances.

Garganta, Júlio (2009). “Trends of tactical performance analysis in team sports: bridging the gap between research, training and competition.” In: *Revista Portuguesa de Ciências do Desporto* 9.1, pp. 81–89.

Garganta, Júlio and Jean Francis Gréhaigne (1999). “Abordagem Sistêmica Do Jogo De Futebol: Moda Ou Necessidade?” In: *Movimento (ESEFID/UFRGS)* 5.10, pp. 40–50. DOI: 10.22456/1982-8918.2457.

Gibson, J. (1979). *The ecological approach to visual perception*. Boston: Houghton, Mifflin and Company.

Gómez-Jordana, Luis et al. (2019). “Landscapes of passing opportunities in Football – where they are and for how long are available ?” In: *Barça Sports Analytics Summit-2nd edition At: Camp Nou- Barcelona*. November, pp. 1–14.

Gréhaigne, J.F., B. Mahut, and A. Fernandez (2001). “Qualitative observation tools to analyse soccer”. In: *International Journal of Performance Analysis in Sport* 1.1, pp. 52–61. DOI: 10.1080/24748668.2001.11868248.

Gréhaigne, Jean Francis, Daniel Bouthier, and Bernard David (1997). “Dynamic-system analysis of opponent relationships in collective actions in soccer”. In: *Journal of Sports Sciences* 15.2, pp. 137–149. DOI: 10.1080/026404197367416.

Gudmundsson, Joachim and Michael Horton (2017). “Spatio-temporal analysis of team sports”. In: *ACM Computing Surveys* 50.2. DOI: 10.1145/3054132. arXiv: 1602.06994.

Headrick, Jonathon et al. (2012). “Proximity-to-goal as a constraint on patterns of behaviour in attacker–defender dyads in team games”. In: *Journal of Sports Sciences* 30.3, pp. 247–253. DOI: 10.1080/02640414.2011.640706.

Heras-Escribano, Manuel and Manuel de Pinedo-García (2018). “Affordances and landscapes: Overcoming the nature-culture dichotomy through niche construction theory”. In: *Frontiers in Psychology* 8.JAN, pp. 1–15. DOI: 10.3389/fpsyg.2017.02294.

Hughes, C. (1990). *The winning formula*. Collins.

Jokuschies, Nina, Vanessa Gut, and Achim Conzelmann (2017). “Systematizing coaches ’ ‘ eye for talent ’: Player assessments based on expert coaches ’ subjective talent criteria in top-level youth soccer”. In: October. DOI: 10.1177/1747954117727646.

Kim, S. (2004). “Voronoi Analysis of a Soccer Game”. In: *Nonlinear Analysis: Modelling and Control* 9.3, pp. 233–240.

Link, Daniel and Martin Hoernig (2017). “Individual ball possession in soccer”. In: *PLoS ONE* 12.7, pp. 1–15. DOI: 10.1371/journal.pone.0179953.

Link, Daniel, Steffen Lang, and Philipp Seidenschwarz (2016). "Real time quantification of dangerousity in football using spatiotemporal tracking data". In: *PLoS ONE* 11.12, pp. 1–16. DOI: 10.1371/journal.pone.0168768.

Lucey, Patrick et al. (2014). ""Quality vs Quantity": Improved Shot Prediction in Soccer using Strategic Features from Spatiotemporal Data". In: *Proc. 8th Annual MIT Sloan Sports Analytics Conference*, pp. 1–9.

Mateus, J. (2005). "In pursuit of an ecological and fractal approach to soccer coaching". In: *Science and Football V : The Proceedings of the Fifth World Congress on Science and Football,* pp. 561–573.

Memmert, Prof Daniel (2012). "Tactical Creativity in Invasion Games". In.

Nevo, Daniel and Ya'acov Ritov (2013). "Around the goal: Examining the effect of the first goal on the second goal in soccer using survival analysis methods". In: *Journal of Quantitative Analysis in Sports* 9.2, pp. 165–177. DOI: 10.1515/jqas-2012-0004. arXiv: 1207.6796.

Okabe, A., B. Boots, and K. Sugiharam (2000). *Spatial Tessellations: Concepts and Applications of Voronoi Diagrams*. (2nd editi. Wiley.

Pardo, Pau (2020). "Creating a Model for Expected Goals in Football using Qualitative Player Information". PhD thesis. Universitat Politècnica de Catalunya.

Passos, Pedro, Duarte Araújo, and Keith Davids (2016). "Competitiveness and the process of co-adaptation in team sport performance". In: *Frontiers in Psychology* 7.OCT, pp. 1–5. DOI: 10.3389/fpsyg.2016.01562.

Pol, Rafel et al. (2020). "Training or Synergizing? Complex Systems Principles Change the Understanding of Sport Processes". In: *Sports Medicine - Open* 6.1. DOI: 10.1186/s40798-020-00256-9.

Pollard, Richard, Jake Ensum, and Samuel Taylor (2004). "Estimating the probability of a shot resulting in a goal: The effects of distance, angle and space". In: *International Journal of Soccer and Science* 2.1, pp. 50–55.

Pratas, J Maria, A Volossovitch, and A Isabel Carita (2018). "Goal scoring in elite male football: A systematic review". In: *Journal of Human Sport and Exercise* 218.1, pp. 218–230. DOI: 10.14198/jhse.2018.131.19.

Queiroz, C. (1986). *Estrutura e Organização dos Exercícios em Futebo*. Lisboa: Federação Portuguesa de Futebol.

Raab, Markus (2010). "Decision making in sports: Influence of complexity on implicit and explicit learning". In: *I* June 2009, pp. 511–564.

Rathke, Alex (2017). "An examination of expected goals and shot efficiency in soccer". PhD thesis. DOI: 10.14198/jhse.2017.12.proc2.05.

Reed, E. (1996). *Encountering the World: Toward an Ecological Psychology*. New York: Oxford University Press.

Rein, Robert, Dominik Raabe, and Daniel Memmert (Oct. 2017). ""Which pass is better?" Novel approaches to assess passing effectiveness in elite soccer". In: *Human Movement Science* 55, pp. 172–181. DOI: 10.1016/j.humov.2017.07.010.

Rothwell, Martyn, Keith Davids, and Joseph Stone (2018). “Harnessing Socio-cultural Constraints on Athlete Development to Create a Form of Life”. In: *Journal of Expertise* 1.1, pp. 1–13.

Rothwell, Martyn, Keith Davids, Joseph A Stone, et al. (2020). “A Department of Methodology Can Coordinate Transdisciplinary Sport Science Support”. In: *Journal of Expertise* 3.1, pp. 55–65.

Rowlinson, Andrew (2020). “Football Shot Quality: Visualizing the Quality of Soccer/ Football Shots”. Master’s Thesis. Aalto University School of Business.

Santos, Sofia, Robyn L. Jones, and Isabel Mesquita (2013). “Do coaches orchestrate? the working practices of elite portuguese coaches”. In: *Research Quarterly for Exercise and Sport* 84.2, pp. 263–272. DOI: 10.1080/02701367.2013.784722.

Seabra, F and Epbt Dantas (2006). “Space definition for match analysis in soccer”. In: *Education* 6, pp. 97–113.

Silva, Pedro et al. (2013). “Shared knowledge or shared affordances? insights from an ecological dynamics approach to team coordination in sports”. In: *Sports Medicine* 43.9, pp. 765–772. DOI: 10.1007/s40279-013-0070-9.

Spearman, William (2018). “Beyond Expected Goals”. PhD thesis, pp. 1–17.

Taki, Tsuyoshi and Jun ichi Hasegawa (2000). “Visualization of dominant region in team games and its application to teamwork analysis”. In: *Proceedings of Computer Graphics International Conference, CGI*, pp. 227–235. DOI: 10.1109/cgi.2000.852338.

Taki, Tsuyoshi and Jun-ichi Hasegawa (2000). “Quantitative measurement of teamwork in ball games using dominant region”. In: *ISPRS J Photogramm* XXXIII.1992, pp. 125–131.

Teodorescu, L. (1984). *Problemas de teoria e metodologia nos jogos desportivos*. Ed. by Ed. Horizonte. Lisboa.

Thorpe, R., D. Bunker, and L. Almond (1986). *Rethinking games teaching*. Department of Physical Education and Sport Science. Loughborough : University of technology.

Travassos, B. et al. (2014). “Eco-Dynamics Approach to the study of Team Sports Performance”. In: *The Open Sports Sciences Journal* 3.1, pp. 56–57. DOI: 10.2174/1875399x010030100056.

Turvey, M. T. (2007). “Action and perception at the level of synergies”. In: *Human Movement Science* 26.4, pp. 657–697. DOI: 10.1016/j.humov.2007.04.002.

Vilar, Luís et al. (2013). “Ecological dynamics as an alternative framework to notational performance analysis”. In: *Complex Systems in Sport*. Routledge, pp. 255–266.

# Applications to coaching and general discussion

# Chapter 8

# Performance analysis of the *in-possession* football team supported by Voronoi diagrams

Caldeira, N., Lopes, R.J. & Araújo, D.

## Abstract

This chapter includes three practical examples of the possible use of spatial quantifications for match performance analysis by football coaches, based on Voronoi diagrams tools. In these examples, the team *in possession* of the ball is the focus, situating the analysis at three different levels: a) the ball carrier; b) the teammates of the ball carrier; and c) the overall team functional degrees of freedom configuration. In an essentially practical reflection, the examples are presented as a way to establish a link between the coach's point of view and what the applied research could add to his/her activity and knowledge, through the positional data extracted from players tracking processes.

## Keywords

Ball carrier, Penetrative pass, Team configuration, Team synergies

## 8.1 Introduction

During a football match, players' interactions originate team collective synergies Gonçalves et al., 2018 based on players' perception of the playing space and their intentionality towards task goal (Gold, 1992). Voronoi diagrams (Kim, 2004) can be used to capture the properties of team synergies (Araújo and K. Davids, 2016), at different scales, in a methodologically coherent way. In fact, due to their simple way of assessing the *dominant regions* (Taki and Hasegawa, 2000) of the players in a game, in this chapter, we exemplify how the measures based on *Voronoi diagrams* (VD) can be applied in coaches practical activities, especially regarding team's tactical performance analysis. Going beyond other metrics that focus on the team from a *holistic* approach (Schöllhorn, 2003), the VD allow measuring not only the *dominant space* for each player (i.e., the synergy property of "*division of labour*") but also the overall territorial "*rapport de forces*" between the two teams (J. Gréhaigne, Godbout, and Zera, 2011).
From the same VD of a given moment, is possible to extract the "Sum of Voronoi Areas" that captures the team's global territorial dominance from a holistic point of view (chapter 4). But is also possible to focus on a local scale to extract the parameters of the "Finishing Space Value" model (chapter 7). The examples of this chapter refer to the simultaneous use of the different metrics extracted from VD, to support football coaches' analysis of some tactical problems. In fact, in three examples of frequent game situations, the VD provides a characterization of the game landscape in different scales, focusing in this case on the players of the team *in possession* of the ball.

## 8.2 Quantifying the ball carrier spatial landscape

How the ball carrier interacts with the ball raises a series of problems, even before the first contact with it (Rein, Raabe, and Memmert, 2017). The solutions are always dependent on the global match context (Gómez-Jordana et al., 2019) that shapes the perception of affordances for the ball carrier and to the other players to solve such tactical problems (J. F. Gréhaigne, Bouthier, and David, 1997; Renshaw et al., 2016). players' choices are globally constrained by the ball and players' location on the pitch (Headrick et al., 2012), as well as, for example, the match time and result shape all players' intentionality (Silva, 2014).

Figure 8.1 illustrates, in a sequence of four moments, the decision-making behaviour of the ball carrier, from the reception of the ball to his passing action to a colleague (in the left wing). Diagram A of Figure 8.1 reproduces the positioning of all players on the pitch that allow a comfortable space (about $128m^2$ in his Voronoi cell area) to the ball carrier (a *Left Center Midfielder*, or CML, of the blue team. Identified with the number 10, in the shaded zone), this diagram A represents the instant when he decides for an *oriented reception*. This technical gesture, controlling the ball to the opposite side of where it appears (yellow arrow), is only possible if the ball carrier perceives enough room to do it, even being in the *interior* of the "*effective playing space*" (EPS) (J. F. Gréhaigne, Bouthier, and David, 1997), where each player dominated spaces is naturally and usually smaller than in the exterior of the EPS. In diagram B (of the same Figure 8.1, reproducing an instant taken about 2 seconds later), it is possible to see that, at the next touch on the ball, the area of the Voronoi cell of the ball carrier remains relatively stable (132 m2). The CML decided then to approach the offensive goal and the areas with a lower density of opponents, which portrays an important individual tactical notion that the top players incorporate into the current game of progressing with the ball whenever there is *enough* dominated space for it. In diagram C (of the same figure 8.1) the space of progression to the opposing target area becomes reduced, because although the value of the ball carrier's Voronoi area increases, its relative position within the respective cell is changed by the approach of the nearest opponent (as an important relativization procedure mentioned in chapter 7), which is now only about 3 meters away. As referred to in chapter 7, it is important to situate each player within its cell of Voronoi, and the distance to the nearest neighbour is a simple way of doing so. In this case the small distance constrains the ball carriers' space of progression towards the opposing target area.

Thus, from the limitation of the space of progression imposed by the approach of an opponent emerges the ball carrier's decision to don't continue the dribble in the interior of EPS. Such a decision would imply an increased risk to assume a *1vs1* situation. Consequently, in the next contact with the ball, the decision of the ball carrier was to make a pass to his colleague (the Left Back, identified with the number 3 in Figure 8.1), who has not only a comfortable $450m^2$ in his Voronoi cell but also has his closest opponent at 10 meters. This sequence of images illustrates how Voronoi diagrams can be used to quantify each player's *dominated space*, taking into consideration the distance for the nearest neighbour (see chapter 7). In fact, in this example, we can say that the option for an oriented ball reception implies a sufficient value of the player's respective Voronoi area, which even if it cannot be defined in an absolute way (as it is related to the technical skills of each player), follows the basic assumption that the smaller it will be, the greater the probability of the respective player to lose the ball. On the contrary, deciding to pass to a teammate who does not have *enough* "dominated space", will lead to an increased difficulty to perform good ball control (reception), and, consequently, to a higher probability to lose the ball. This simple

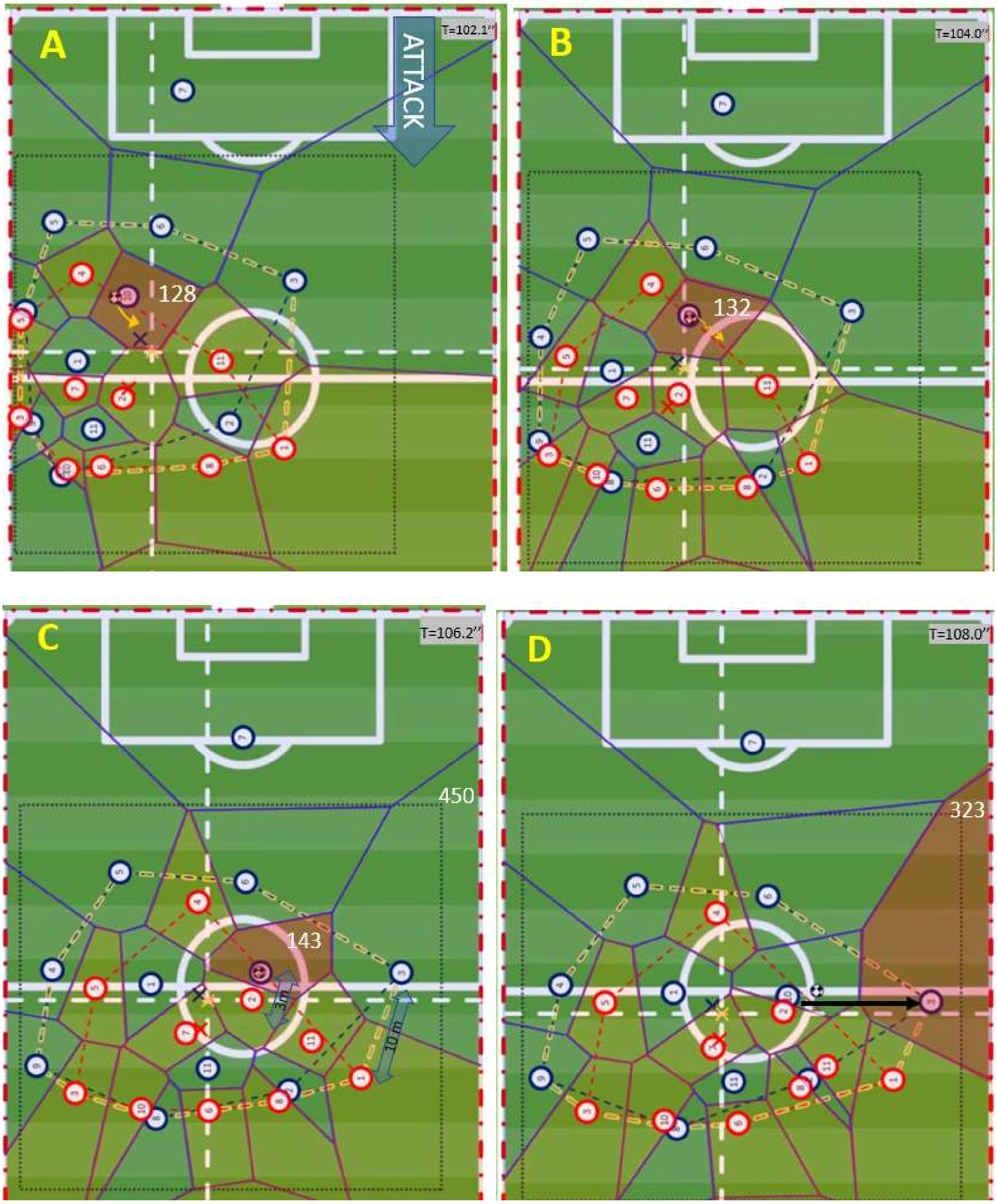



**Figure 8.1:** Sequence of the ball carrier decisions, through corresponding Voronoi diagrams
*Note:* Illustration of a sequence of moments (A, B, C and D) between the oriented reception and the pass by a player (number 10, of the "blue team"), where we can see how the "dominated space", measured through the "Voronoi area" of each player, can affect the decision making

example illustrates how the dominated space, for the ball carrier himself and his/her perception about the spaces of other teammates, constitute decisive affordances in the decision-making processes that underpin players' interactions. The possibility of using a measure of these same spaces based on *Voronoi diagrams* seems to us a fairly simple route that can be further generalized due to the vulgarization of systems for collecting positional coordinates of players (e.g. through GPS which are already a resource used also by amateur and youth teams), opening doors for an intervention of coaches supported by quantitative data.

## 8.3 Understanding the ball carrier's teammates' tactical problems

Regarding the team in possession, the ten teammates of the ball carrier are constantly facing tactical problems concerning what would be the best location to be in each given instant of the game. Through the 6 diagrams of Figure 8.1, we exemplify how we can interpret the decisions of a player based on Voronoi diagrams metrics, in this case analysing the (inter)actions of the Right Back (RB) of the blue team (number 4).

In the first diagram (A) of Figure 8.1, it is possible to see the smallness of the Voronoi cell of this RB of the blue team (57.4 m2). This circumstance is a consequence, firstly, of his proximity to the teammate with the ball, an Offensive Midfielder (OM), who appears temporarily in the right-wing (identified with the number 11 of the blue team). But also by the position of the nearest opponent between him and the goal (identified with the number 10 of the red team), which is only 3.75 meters apart. In this case, is the Left Central Defender (CBL), as the opponent team maintains a system with three central backs. The following diagrams, taken with an interval of 0.5 seconds, illustrate RB's option in trying to exploit the deep space on his direct opponent's back. Thus, in diagram B, the RB of the blue team is already further away from his teammate with the ball, running towards the back line which allows him to increase his Voronoi cell ($123m^2$), although he must momentarily approach his nearest opponent (2.9 meters). The perception that the RB will be able to gain the space behind his direct opponent in the immediate instant, leads the ball carrier (OM) to decide to make a *penetrative pass* to the free space (Sotudeh, 2021), which is depicted in diagram C. In this diagram C is already visible the increase of the "Voronoi cell" of the RB ($217.8m^2$) despite the short distance he maintains to his nearest opponent ($1.65meters$), and how this space gain has a growing trend in the immediate instants due to the speed differences between the two players ($7.15m/s$ for the blue team player and just $4.21m/s$ for the red team player). In the following diagram (D), it becomes apparent that the RB of the blue team (number 4) will gain a positional advantage over the CBL of the red team (number 10), which translates into an increase in their Voronoi area ($247.7m^2$). In the next moments illustrated in diagrams E and F, this advantage will allow the RB (4) to approach the opponent's goal line, being able to shoot or cross but breaking, in any case, the defensive organization of the opponent's team thanks to the interaction (synergy) with his teammate. This is an example of how a player without the ball from the *in possession* team dealt with the generic tactical problem of where to move and how. Working together with a colleague, synergistically, they were able to act accordingly

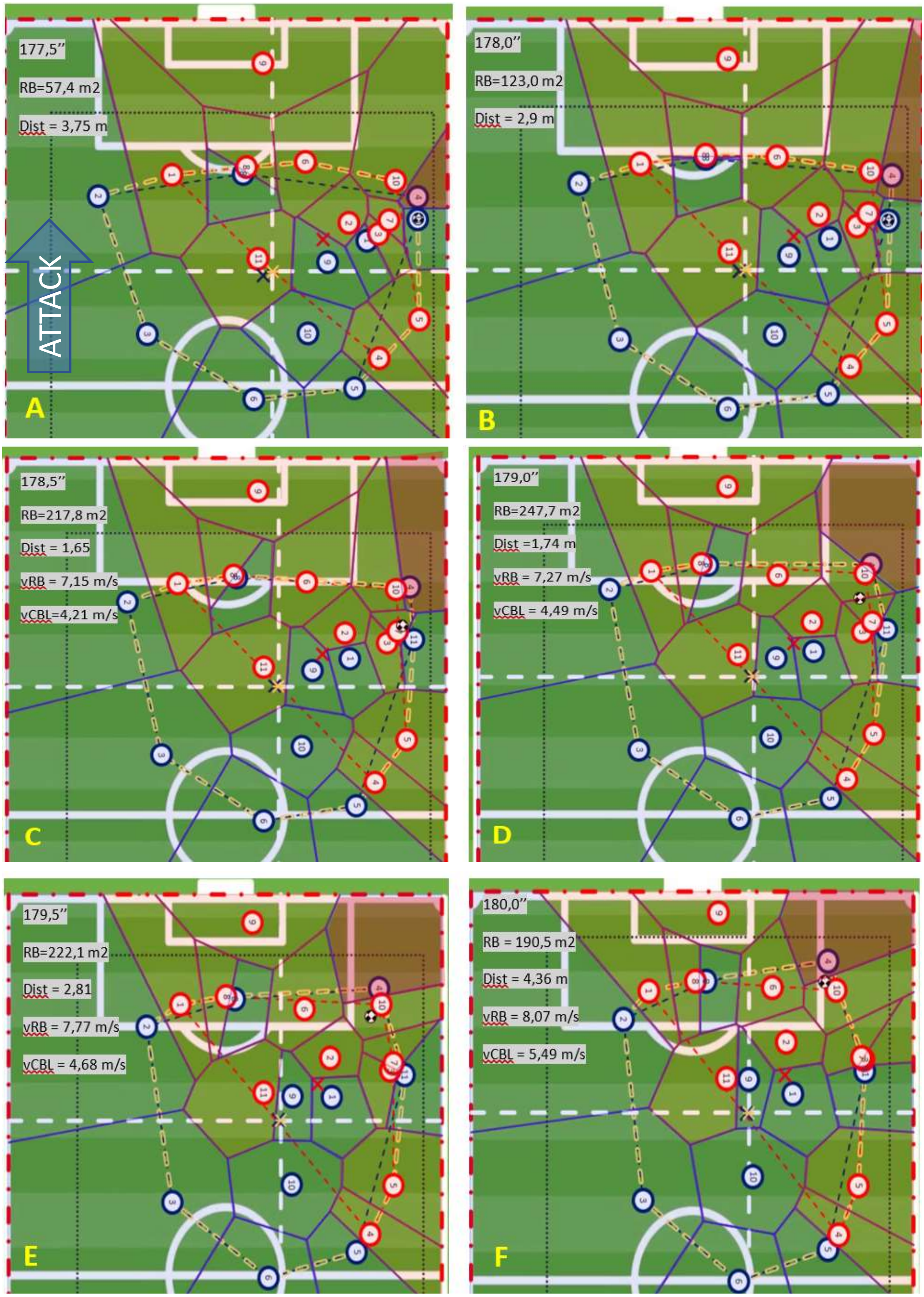



**Figure 8.2:** Sequence of Voronoi diagrams illustrating the exploitation of the space behind the defensive line.
*Note:* Illustration of the (inter)action between two players of the blue team, i.e., the ball carrier (number 11) and his teammate (a right back", with the number 4)

to the changes in the playing landscape (quantifiable, as we argued here, through successive Voronoi diagrams), deciding according to their tactical intentions. In this case, we focus our attention on the player who aims to attack the opponent's goal, but we could also do so from the perspective of the team that is defending. As referred by Corning (2018), synergies are "value-neutral". In this case, this is clear analyzing the contrary problem that was experienced by the player identified with the number 10 of the red team (as mentioned, a central defender, in a defensive organization with three central backs, who is in this situation defending in the left side corridor). In fact, the space to receive the ball behind the defensive line and the *positive functional effect* from the blue team perspective (space to cross or shoot), emerged from his interaction with teammates and opponents. For example, from the number 10 (of the red team) decision to get closer to the opponent (leaving a greater distance to his own goal and his closest colleague). Therefore, the same metrics used to interpret quantitatively the decision of the players *in possession* (blue team), can also be used to capture the *negative functional effects* on the opposite *out of possession* team.

## 8.4 The global (self-)-coordination of the *in possession* team

The collective action of a football team during the i*n possession* phase is supported by a great purpose (to win) assumed as common by its elements and that emerges not only from the regulation, but also from the cultural logic of the game (Rothwell, Keith Davids, and Stone, 2018) in a given context (society in general, and, particularly, a team culture). It is this cultural background that shapes the evolution of a style or a specific way to play in a given environment (Fernandez-Navarro et al., 2018).

In this way, at the high-level, the individual displacements of the players appear in our eyes as having remarkable (self-)coordination. For example, with instant adaptations to the perception of which element is closest to the ball and which will be able to control it. Equally, teams globally adjust the collective configuration (Dodel, Tognoli, and J. A. Kelso, 2020) to maintain the highest possible of passing possibilities (see chapter 5). Almost as if all elements were part of a "super-organism" (Duarte et al., 2012), each player of the *in possession* team seek to contribute to the practical materialization of the team's strategic intentions (for example, regarding how to move the ball forward in the direction of the opponent's net). In this sense, the search for the best solutions at every instant to make the ball circulate through the pass depends largely on the perception of the space available for each element. It becomes then a collective challenge to, assuring territorial dominance (Garcia-Madurga, Grilló-Méndez, and Esteban-Navarro, 2020), find the best paths towards the opponent's goal. The sequence of passes will therefore seek to find a colleague with a high probability of scoring (a high "Finishing Space Value", see chapter 7). Conceptually, is possible to admit that the most successful paths to the opponent's goal may come out reinforced in a logic of a certain "stigmergy" (Crowston et al., 2017; Sharma and Patil, 2017). In this collective challenge of the in possession team to approach the opponent's goal, the objective of finding spaces for progression (Fernández, Bornn, and Cervone, 2019) depends not on individual actions disconnected from each other, but on a common operational logic that guarantees. It is in this sense that the teams seek to ensure a given global configuration that emerges from the instant positioning of their elements

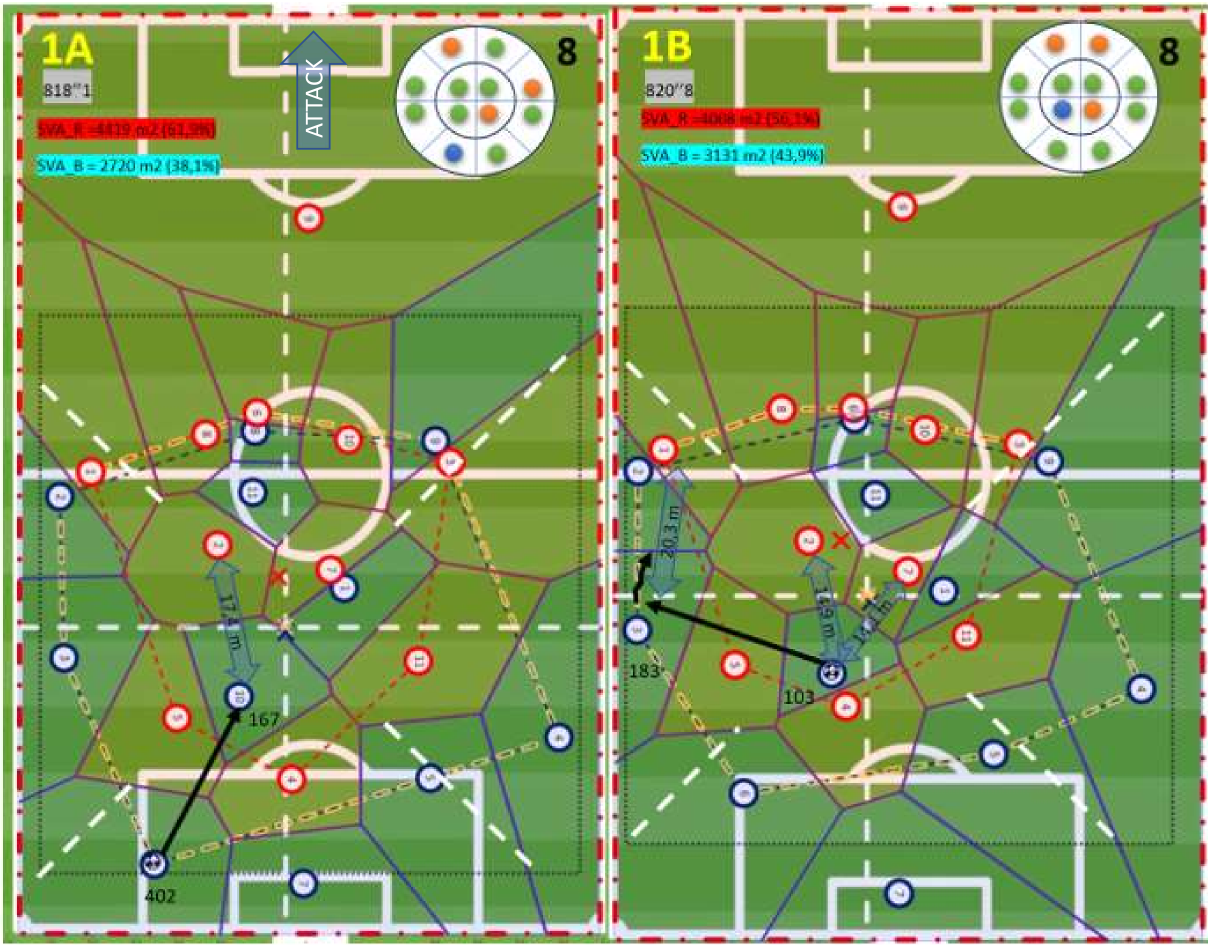



**Figure 8.3:** Start of a sequence of diagrams (A and B), illustrating an “in possession team” overall configuration and fDOF, during the first stage of an “effective possession episode”.

*vis-à-vis* the opponents, and that allows the maximization of the individual spaces to the ball carrier and their possibilities of connection through the pass, especially in their vicinity. Much of the work of the coaches and their technical teams then involves trying to ensure that the members of their teams are able to coordinate with others, to present a certain level of (self)organization throughout the ball in possession phase. As suggested in chapter 5, is possible to assess the team’s global configuration from the positional data through a quantitative tool with sensitivity to capture the ”*functional degrees of freedom*” (fDOF) of a team as a whole. To illustrate a possible practical application of the proposed methodology, we bring here two small ”possession episodes”, from the same team, but with totally different outcomes. In the first case (Figure 8.3 and Figure 8.3, the 4 diagrams seek to convey the importance of maximizing the number of fDOF at all stages of the offensive process, namely in two moments taken from the first and second construction phases. In this example, an *effective* overall configuration of the team in possession (in blue) enabled the existence of a minimum of 8 fDOF at a time, opening sufficiently wide pass possibilities that successfully contradicted the strategy of ”pressing high” of the opponent team (visible in its more than 60% of SVA).

From a global perspective, it is important to observe not only the number of fDOF available but also their relative location. In this particular, we would like to stress the importance of ensuring the ball carrier (represented by a blue ball in the radar scheme), both exterior and interior passing options in their proximity. In fact, since collective synergies exhibit a degeneracy property, is not generally much important who is the player that will appear in a certain space giving a pass option. Instead, it is important to provide full passing options to the ball carrier, through the team's global coordination. In diagram 1A of Figure 8.3, corresponding to the moment when the Central Back Left (CBL, identified with the number 6, of the blue team) has the ball and starts the offensive construction phase, is possible to observe the configuration of the team in each moment. Showing the illustrative "radar scheme" (see chapter 5), the quadrants of the interior EPS space and the octants of the exterior EPS space showed at least one player (one "*functional degree of freedom*" marked with a green circle), around the ball carrier. This collective configuration allowed the pass from the number 6 to the number 10, having this one a Voronoi cell of $167m^2$ and a distance of more than $17meters$ to his nearest opponent. Thus, in diagram 1B of Figure 8.3, taken from the instant where player no. 10 passes the ball to his colleague no. 3 (Left Back or LB, which has $183m^2$ in his Voronoi cell with the nearest opponent more than $20meters$ away), in a logic of alternating the pass between interior and exterior areas of the EPS. In this way, the blue team members cooperated synergistically to create conditions for the LB to have an important dominated space to progress towards the opponent's goal. This is illustrated in diagram 1C of Figure 8.4, where the collective configuration of the team further maximized the fDOF (now nine), creating an additional possibility of connection. This was achieved mainly due to the action of the Striker (or FW, identified with the number 8), which with a forward vertical run seeks to explore the space in depth, behind the last defensive line of the opponent's team.

It is for this player (FW) that the LB chooses to pass the ball, which has a dominated space of $108m^2$ at that moment, which is enlarged due to the shift in the opposite direction of the Offensive Midfielder (identified with the number 11). This player would also be a good pass option, but he will decide to, without touching it, let the ball pass (in diagram 1D of Figure 8.4) to his more advanced colleague (FW), who still with more space ($229m^2$) was able to finish the play.
However, a team do not always achieve to maximise its fDOF and, consequently, the quality of passing affordances that are available to the ball carrier. This is the case of the next situation (illustrated by Figures 8.5 and 8.5), where the CBL (number 6) shows a sort of precipitation in progressing with the ball before the team (as a whole) has crystallized its configuration with a greater number of fDOF, limiting the likelihood of the possession episode in being successful.

In fact, in diagram 2A of the Figure 8.5, we can see how the CBL, despite having a comfortable Voronoi cell area of 546 m2 and the nearest opponent being more than 15 meters away, chose to move forward with the ball without waiting for the team to achieve a greater number of fDOF (only 6). This is especially relevant in its vicinity (interior zones of the EPS) as is possible to observe by the orange circles in the scheme on radar, meaning an absence of players in these zones of the EPS. His choice to drive the ball forward at great speed (about $5.35m/s$) and the approach of the closest direct opponent (number 4 of the red team), leaves him unable to wait for the release of passing options in these interior zones of the EPS. This is possible to identify in diagram 2B (Figure 8.5), where there is one more *functional degree of*

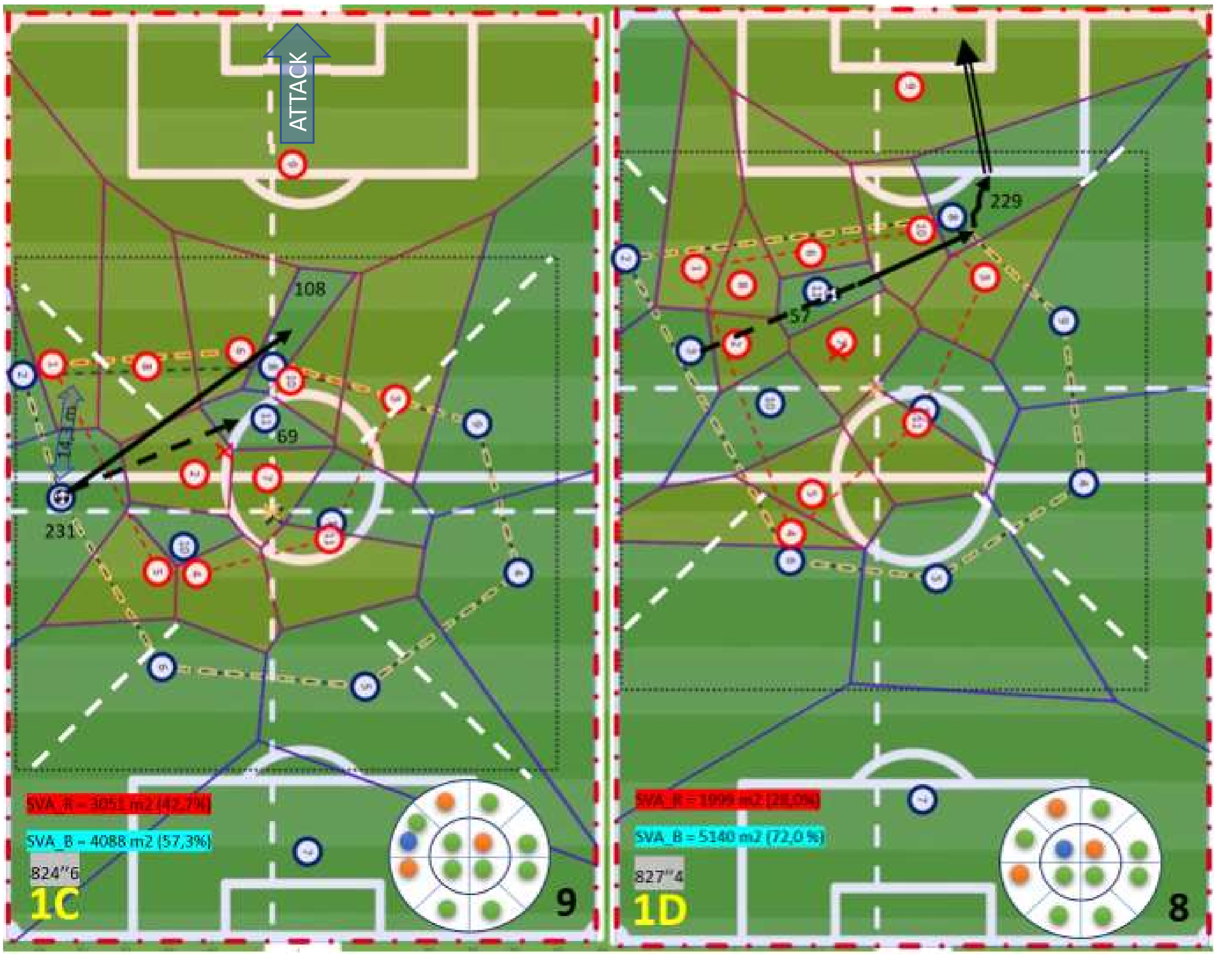



**Figure 8.4:** End of a sequence of diagrams (C and D), illustrating an "in possession" team overall configuration and fDOF, during the conclusion of an "*effective* possession episode".

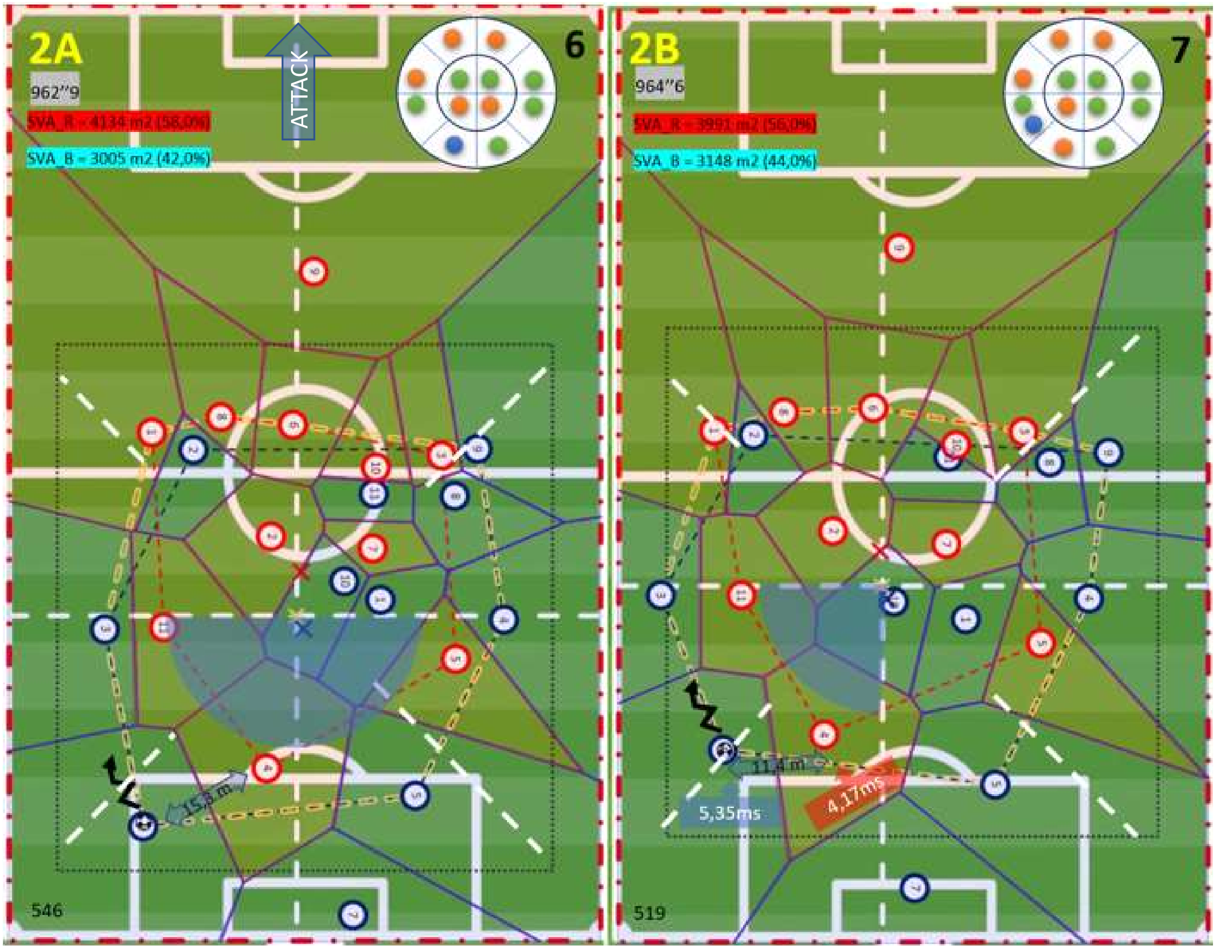



**Figure 8.5:** Start of a sequence of diagrams (A and B), illustrating an "in possession" team overall configuration and fDOF, of an "*non-effective* possession episode".

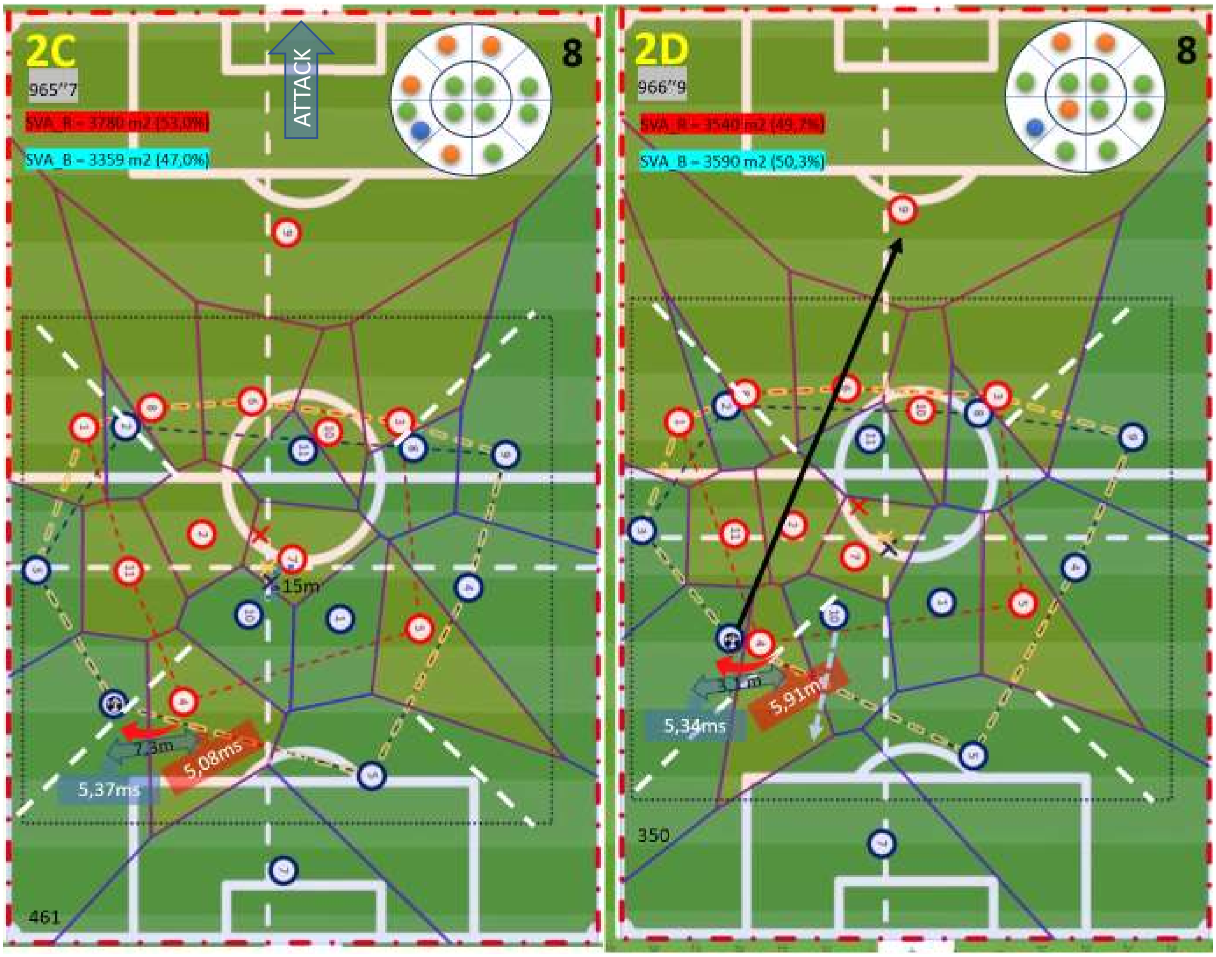



**Figure 8.6:** End of a sequence of diagrams (C and D), illustrating an “in possession” team overall configuration and fDOF, of an “non-effective possession episode”.

*freedom* available (7). However, the impossibility of taking advantage of interior passing options in useful time becomes increasingly evident (diagram 2C of Figure 8.5). At that instant, the increasing fDOF of the team as a whole (8), probably cannot be equated by the ball carrier (CBL), due to the approach of the nearest opponent (7.3 meters in diagram 2C and only 3.1 meters in diagram 2D) and the consequent reduction of its Voronoi cell area (461 and $350m^2$, respectively).

By dribbling the ball with a probably excessive speed, and facing the direct opponent’s acceleration ($5.91 m/s$), the CBL adopted a more *”defensive”* posture and merely sent the ball forward, causing the team to lose the ball possession(diagram 2D). It should be noted that realizing the path of his colleague CBL with the ball and the possible risk of him losing his possession, we see a shift towards his goal of number 10 (CML). Thus, occupying a zone closer to his own goal, this player displacement showed a reciprocal compensation that will increase the balance of the team at the time of the loss and in its transition to an *out of possession* phase.

Being the two “possession episodes” in two relatively close moments of the same match (only separated by just over 2 minutes) and performed by the same team, it was our intention to illustrate how the collective team configuration influences individual decisions, as the individual decisions influence *circularly* the collective configurations of a team as a whole. Thus, from a practical point of view, it is possible to speculate from these examples about the emergence of collective synergies and how they can also be captured by this type of variables that collect the overall team configurations, in a circular process between the element(s) and the whole, expressed in the fDOF of a football team (in this case when in possession).

## 8.5 Conclusion

In football, as a collective sports game (Teodorescu, 1984), each player's decision is embedded in the involvement. In a landscape that is constantly changing, not only because of his/her own action but also due to the concomitant actions of the other elements that are playing with him/her, whether from a cooperative or competitive perspective (Ramírez-López et al., 2020). That is why, to better understand the game of Football (and consequently intervene in it), the observer (e.g., the coach) must go beyond the player's individual sphere, and focus on the cooperative and competitive interactions (J. S. Kelso, D. A. Engstrom, and D. Engstrom, 2006) that are established between players of both teams in opposition. Hence our unequivocal interest in the concept of synergies and how it can be used to deepen our knowledge of the game of football. After all, a team does not seem different from other systems where different parts cooperate to achieve "*functional effects that are jointly created and that are not otherwise attainable*" (Corning, 2018, ch2).

Therefore, the situations illustrated here are only a few examples, at different scales, of the possibilities of quantification using Voronoi-diagrams-based metrics and the interpretation of team synergies from a coach's practical point of view. Supported by measures of dominant spaces (Taki and Hasegawa, 2000) a coach can approach the spaces eventually perceived by their players (Jacques et al., 2007) in the constantly renewed match landscapes that create *ephemeral* affordances (Withagen et al., 2012). Such tactical interpretation, even if using quantitative tools, can contribute to an empathically better understanding of players' decisions and actions, supporting coaches' pedagogical intervention.

## References


Araújo, D. and K. Davids (2016). “Team synergies in sport: Theory and measures”. In: *Frontiers in Psychology* 7.SEP, pp. 1–13. DOI: 10.3389/fpsyg.2016.01449Team.

Corning, Peter (2018). *Synergistic Selection: How Cooperation Has Shaped Evolution And The Rise Of Humankind*. WORLD SCIENTIFIC PUBLISHING CO PTE LTD.

Crowston, Kevin et al. (2017). “Work Features to Support Stigmergic Coordination in Distributed Teams”. In: *Academy of Management Proceedings* 2017.1, p. 14409. DOI: 10.5465/ambpp.2017.14409abstract.

Dodel, Silke, Emmanuelle Tognoli, and J. A.Scott Kelso (2020). “Degeneracy and Complexity in Neuro-Behavioral Correlates of Team Coordination”. In: *Frontiers in Human Neuroscience* 14.September, pp. 1–13. DOI: 10.3389/fnhum.2020.00328.

Duarte, Ricardo et al. (2012). “Sports Teams as Superorganisms”. In: *Sports Medicine* 42.8, p. 1. DOI: 10.2165/11632450-000000000-00000.

Fernández, Javier, Luke Bornn, and Dan Cervone (2019). “Decomposing the Immeasurable Sport: A deep learning expected possession value framework for soccer”. In: *MIT Sloan Sports Analytics Conference*, pp. 1–18.

Fernandez-Navarro, Javier et al. (2018). “Influence of contextual variables on styles of play in soccer”. In: *International Journal of Performance Analysis in Sport* 18.3, pp. 423–436.

Garcia-Madurga, Miguel-Ángel, Ana-julia Grilló-Méndez, and Miguel-Ángel Esteban-Navarro (2020). “Territorial Intelligence , a Collective Challenge for Sustainable Development: A Scoping Review”. In: *Social Sciences* 7.7, p. 126. DOI: doi:10.3390/socsci9070126.

Gold, Christopher M (1992). “The Meaning of “ Neighbour ””. In: *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space*. Springer, Berlin, Heidelberg, pp. 220–235.

Gómez-Jordana, Luis et al. (2019). “Landscapes of passing opportunities in Football – where they are and for how long are available ?” In: *Barça Sports Analytics Summit-2nd edition At: Camp Nou- Barcelona*. November, pp. 1–14.

Gonçalves, Bruno et al. (2018). “Changes in Effective Playing Space When Considering Sub-Groups of 3 to 10 Players in Professional Soccer Matches”. In: *Journal of Human Kinetics* 62.1, pp. 145–155. DOI: 10.1515/hukin-2017-0166.

Gréhaigne, J., P. Godbout, and Z. Zera (2011). “How the “ rapport de forces ” evolves in a soccer match : the dynamics of collective”. In: *Rev. Psicol. Deporte* 20, pp. 747–765.

Gréhaigne, Jean Francis, Daniel Bouthier, and Bernard David (1997). “Dynamic-system analysis of opponent relationships in collective actions in soccer”. In: *Journal of Sports Sciences* 15.2, pp. 137–149. DOI: 10.1080/026404197367416.

Headrick, Jonathon et al. (2012). “Proximity-to-goal as a constraint on patterns of behaviour in attacker–defender dyads in team games”. In: *Journal of Sports Sciences* 30.3, pp. 247–253. DOI: 10.1080/02640414.2011.640706.

Jacques, Julio Cezar Silveira et al. (2007). "Understanding people motion in video sequences using Voronoi diagrams: Detecting and classifying groups". In: *Pattern Analysis and Applications* 10.4, pp. 321–332. DOI: 10.1007/s10044-007-0070-1.

Kelso, J. S., D. A. Engstrom, and D. Engstrom (2006). *The complementary nature*. MIT press.

Kim, S. (2004). "Voronoi Analysis of a Soccer Game". In: *Nonlinear Analysis: Modelling and Control* 9.3, pp. 233–240.

Ramírez-López, C. et al. (2020). "Coopetition: cooperation among competitors to enhance applied research and drive innovation in elite sport". In: *British Journal of Sports Medicine.* 2017.1, pp. 1–9.

Rein, Robert, Dominik Raabe, and Daniel Memmert (Oct. 2017). ""Which pass is better?" Novel approaches to assess passing effectiveness in elite soccer". In: *Human Movement Science* 55, pp. 172–181. DOI: 10.1016/j.humov.2017.07.010.

Renshaw, Ian et al. (2016). "Why the Constraints-Led Approach is not Teaching Games for Understanding: a clarification". In: *Physical Education and Sport Pedagogy* 21.5, pp. 459–480. DOI: 10.1080/17408989.2015.1095870.

Rothwell, Martyn, Keith Davids, and Joseph Stone (2018). "Harnessing Socio-cultural Constraints on Athlete Development to Create a Form of Life". In: *Journal of Expertise* 1.1, pp. 1–13.

Schöllhorn, W. (2003). "Coordination dynamics and its consequences on sports". In: *International Journal of Computer Science in Sport* 2.2, pp. 40–46.

Sharma, Shanu and Koumudi Patil (2017). "Call of Survival: Stigmergy for Matters of Concern". In: *Design Journal* 20.sup1, S2883–S2893. DOI: 10.1080/14606925.2017.1352799.

Silva, Pedro (2014). "Shaping Tactical Behaviours in Football: An Ecological Dynamics Approach". PhD thesis. Universidade do Porto, p. 214.

Sotudeh, Hadi (2021). "Potential Penetrative Pass ( P3 )". In: *Statsbomb conference 2021*, pp. 1–13.

Taki, Tsuyoshi and Jun ichi Hasegawa (2000). "Visualization of dominant region in team games and its application to teamwork analysis". In: *Proceedings of Computer Graphics International Conference, CGI*, pp. 227–235. DOI: 10.1109/cgi.2000.852338.

Teodorescu, L. (1984). *Problemas de teoria e metodologia nos jogos desportivos*. Ed. by Ed. Horizonte. Lisboa.

Withagen, Rob et al. (2012). "Affordances can invite behavior: Reconsidering the relationship between affordances and agency". In: *New Ideas in Psychology* 30.2, pp. 250–258. DOI: 10.1016/j.newideapsych.2011.12.003.

# Chapter 9

# Performance analysis of the *out-of-possession* football team supported by Voronoi diagrams

Caldeira, N., Lopes, R.J. & Araújo, D.

## Abstract

This chapter includes two practical examples of the possible use by football coaches of spatial quantifications based on Voronoi diagrams (VD), for the purpose of match performance analysis. In an essentially practical approach, the examples are presented as a way to establish a link between the coach's tactical point of view and what the applied research of this thesis could add to his/her activity and knowledge, through the positional data extracted from players tracking processes and compound VD metrics. In these examples, the team *out possession* is the focus, in two different levels: a) the whole team coordination in a high press situation; and b) the individual local decision of a first defensive line member.

## Keywords

High-press, Individual Pressure, Covering, Team synergies

## 9.1 Introduction

For the players of the team that does not have the ball (*out of possession*), the main questions are related to the possible means to recover the ball, but also to disturb the opponent's team progression towards their own goal. This implies a coordinated individual effort of the "out of possession" players' to oppose the ambition of territorial dominance of the opponent's team, reducing the "dominated space" (Taki and Hasegawa, 2000) of each player of the team "in possession". In this realm, it is especially important the space and time pressures that are perceived by the *ball carrier* and their nearest teammates, hampering their decisions and actions (Afonso, Garganta, and Mesquita, 2012). However, the idea of reducing the opponent's dominated space raises tactical problems to solve instantly for the players of the team *out of possession* (J. F. Gréhaigne, Bouthier, and David, 1997). For example, if the team should collectively advance on the field and press the opponent as *high* as possible (Low, Boas, et al., 2018) or stay *closer* to the goal and protect it a greater players concentration. If they advance and press high, they increase the chances of provoking a technical error and recovering the ball closer to the opponent's goal Hughes and Lovell, 2019. But also increases the difficulties to keep the team compact because the only way to do so is to advance all its elements (including the defensive line and even the goalkeeper). The collective option to press high (Low, Boas, et al., 2018) is a tactical-strategic response that increases the likelihood of leaving free spaces between the sectors and between the defensive sector and the goalkeeper, but which also prevents all the risks of defending low in the vicinity of their own goal 7 and, thereby, to let the opponent the opportunity to dominate the field 4. The overall "pressure strategy" of a team is therefore a collective problem that coaches and their players need to face in the foresight analysis that precedes many matches. The strategic options (Oliveira and Tavares, 1996) agreed upon and rehearsed by a team in the pre-match training sessions, will depend on what is to be seen as the *balance of forces* (J. Gréhaigne, Godbout, and Zera, 2011) on the ground. For example, in individual terms, the running and decision speed of a central defender *versus* the same characteristics of his/her direct opponent (attacker).

In our view, the strategic options (Oliveira and Tavares, 1996) taken prior to a match will constitute an important constraint of the tactical-technical players' decisions that occur at each moment during the game (1986). These strategic constraints will also shape the players' decisions during the match, e.g. if collectively pressing high is the most appropriate solution for each moment in which the opponent has the ball far from their own goal. However, as in other situations, the out of possession collective macro behaviour influences and (circularly) are influenced by the displacements and (micro) actions of each one of its players (Duarte Araújo et al., 2016). This is the case of a central defender when he/she must choose between "go out" and reduce the distance to their direct opponent or maintaining alignment with the other sector teammates ("*defensive line*"). If he/she "go out" to reduce that distance, the "dominated space" to the direct opponent to shoot or to easily progress towards his/her net will decrease. But it also implies that the space behind his/her back will increase, augmenting the probability that can be taken advantage of by the movements of other opposing players. It is an authentic tactical *dilemma* that is constantly also present in the performance of other players. This is evident in *side backs* tactical dilemmas because if they do not shorten the distance to their direct opponent's (e.g., a winger), they open room to an easier ball control that can give the time to increase their threat level regarding the following actions (for example, to cross or to accelerate to a 1vs1 situation. However, being too close to the direct opponent potentially reduces the opponent's "space dominance", but they are potentially losing the bond with their closer teammates. From a synergistic point of view, the solution to these dilemmas and tactical problems lies in coordinating individual actions with their sector colleagues (or the immediate line in front or behind) to provide a mutual "defensive coverage" (Ribeiro et al., 2019). It is demanded a certain degree of displacement synchronization, even if in different directions (López-felip and Frank, 2017), to prevent the emergence of spaces that could be potentially explored by the *in possession* team. In this realm, finding operational means to quantify the effectiveness (and efficiency) of players' decisions (individually and collectively) is an important quest for football coaches and sports scientists. These two following sections (9.2 and 9.3) aims to demonstrate how a coach can use the tools previously referred to in this thesis, to assess players' interactions and their *functional effects*. Through Voronoi diagrams-based metrics, we exemplify how can we interpret synergies (emerging from players' interactions) in two different scales: a) the overall team coordination during the high press; and b) the individual tactical dilemma of a central defender.

## 9.2 Team coordination during a "high-pressing" tactical-strategy

The tactical problems that arise in the context of the football game are not exclusive to the phases in which a given team retains ball possession. During phases when a team is *out of possession*, players must coordinate their displacements to implement a common strategy, dealing with the tactical problems that emerge from the simultaneous *collective intention* (Searle, 1990) of protecting their goal and seeking to regain ball possession. This is the case of the so-called pressing tactics (Low, Rein, et al., 2021), where the team as a whole seeks to restrict the opponent's spaces to advance while seeking to regain ball possession near the opposing net. However, it is a tactical-strategy collective action not exempted from risks (Andrienko et al., 2017), because it necessarily implies bigger spaces between sectors (if the team is not able to move up as a block) or an increased distance behind the last defensive line (if their players move forward). From the harmony between risk and benefit (Power et al., 2017) emerges a tactical dilemma with which all the members of the *out of possession* team have to deal in a coordinated way, as illustrated in the sequence of diagrams from Figures 9.1 to 9.4. In this sequence, the blue team will seek to press as high as possible to restrict the spaces to their opponent, which will be visible in their ability to reverse the *territorial dominance* 4 that is normally associated with the team in possession and which in this case is captured through the *Sum of Voronoi Areas* (SVA) 4. In fact, in diagram A (Figure 9.1), which illustrates the moment the red player identified with the number 7 received the ball from a side throw from number 3, we observe the very small Voronoi area of this player ($29.4m^2$) that may have led him to choose to make a pass to his partner (number 2) who is in the interior space with a more "comfortable" Voronoi area of $121.9m^2$. In the following diagram (B of Figure 9.1), we have the Voronoi cells corresponding to the instant that the no. 2 (a center midfielder), seeing as approaching the opponent no. 8 decides to make the pass to his colleague no. 10 (a central defender), who is supporting further behind (Wade, 1998). It is at this moment that the displacements forward of the blue team (*out of possession*) begin to intensify, visible in diagram C (Figure 9.2) where the closest element to the own net is at $38.5 meters$ from the goal line (in diagram B he was at $35.4 meters$). This also corresponds to a progressive decrease in the *territorial dominance* that belongs to the team in possession (red).

Then, in Figure 9.2) (diagram C), the number 10 decides to make a pass to his sector colleague (6) despite having a comfortable area to keep the ball and his position inside the Voronoi cell is still determined by the nearest opponents being about 8.2 and $10.0 meters$, which serves as a stimulus to the strong pressure of his nearest opponent (no. 8 blue). So much so that in the following diagram (D, of Figure 9.2), not only we can observe a rapid decrease in the available area for the no. 6, but we should stress the distance to his closest opponent (only $2.2 meters$ away), leading this player to opt for a safe pass to his goalkeeper (9). At this point, with the pass behind, the last defensive line of the blue team takes advantage to move forward even further, leading to a distance of $44.5 meters$ from its goal line and the closest player, which allowed to leave two opponents off-side, passing the territorial dominance to the blue team (without the players off-side, the SVA is already 52.4% for the blue team).

With each pass behind from the opponent, the blue team takes the opportunity to move forward in a coordinated way, with the Central Forward (8) doing a pressure movement, in a displacement that reaches $5.86 m/s$ (in diagram E of Figure 9.3), towards the goalkeeper of the opposing team, which sees its Voronoi area fall at great speed as a result of the dwindled distance between these two opponents. In this diagram E (Figure 9.3), taken at the time the goalkeeper makes the reception of the ball, it is already evident the passage to a collective *territorial domain* by the blue team (53.7% of the SVA), but also consequently a great distance between the most retreated player and his goal line ($47.8 meters$). In the following diagram F (Figure 9.3), with the nearest opponent just $4 meters$ away and without safe pass lines in the vicinity, the red team goalkeeper chooses to kick a long ball towards his most advanced colleague in the left side corridor (no. 5).

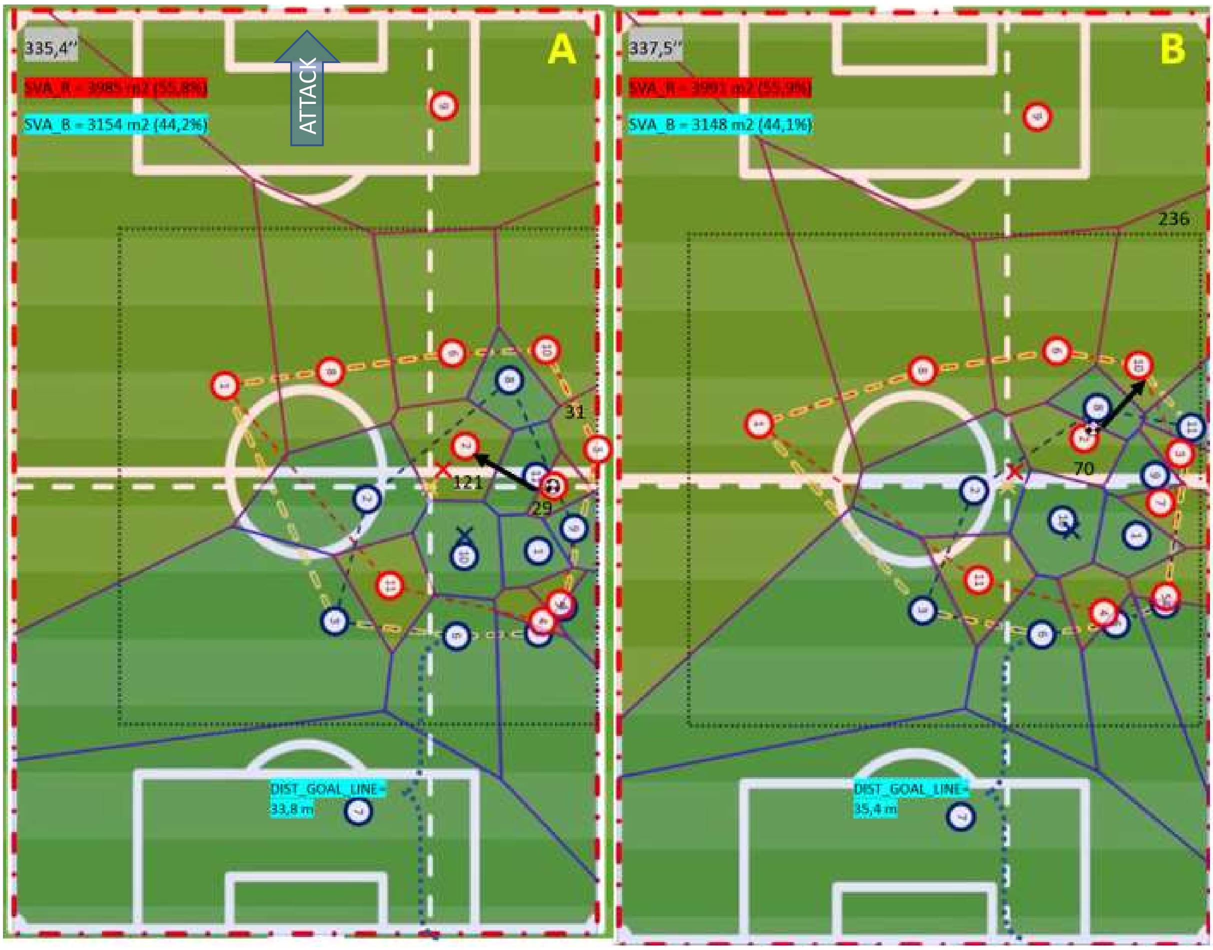



**Figure 9.1:** Start of a sequence of diagrams (A and B) of a collective high-press (by the blue team)

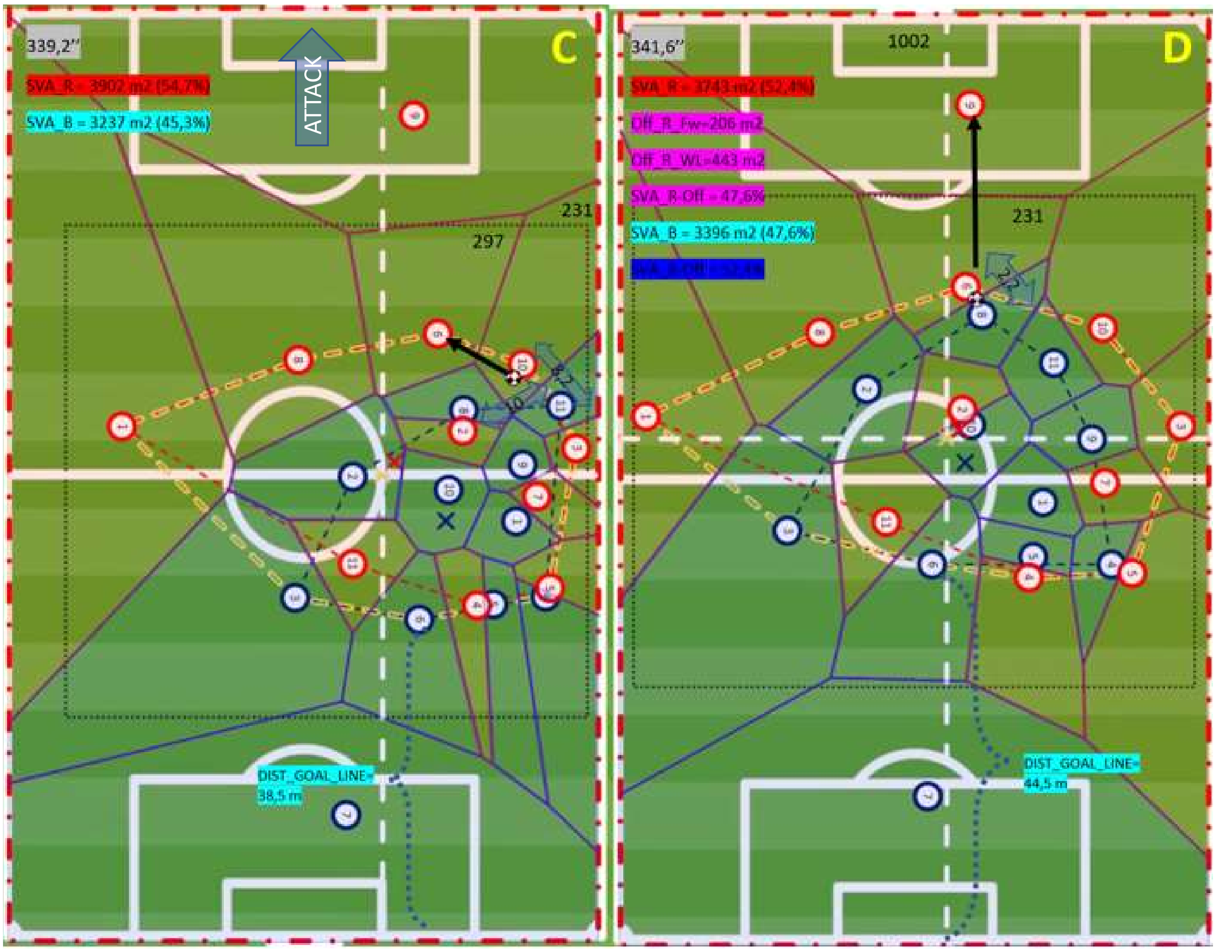



**Figure 9.2:** Continuity of a sequence of diagrams (C and D) of a collective high-press (blue team)

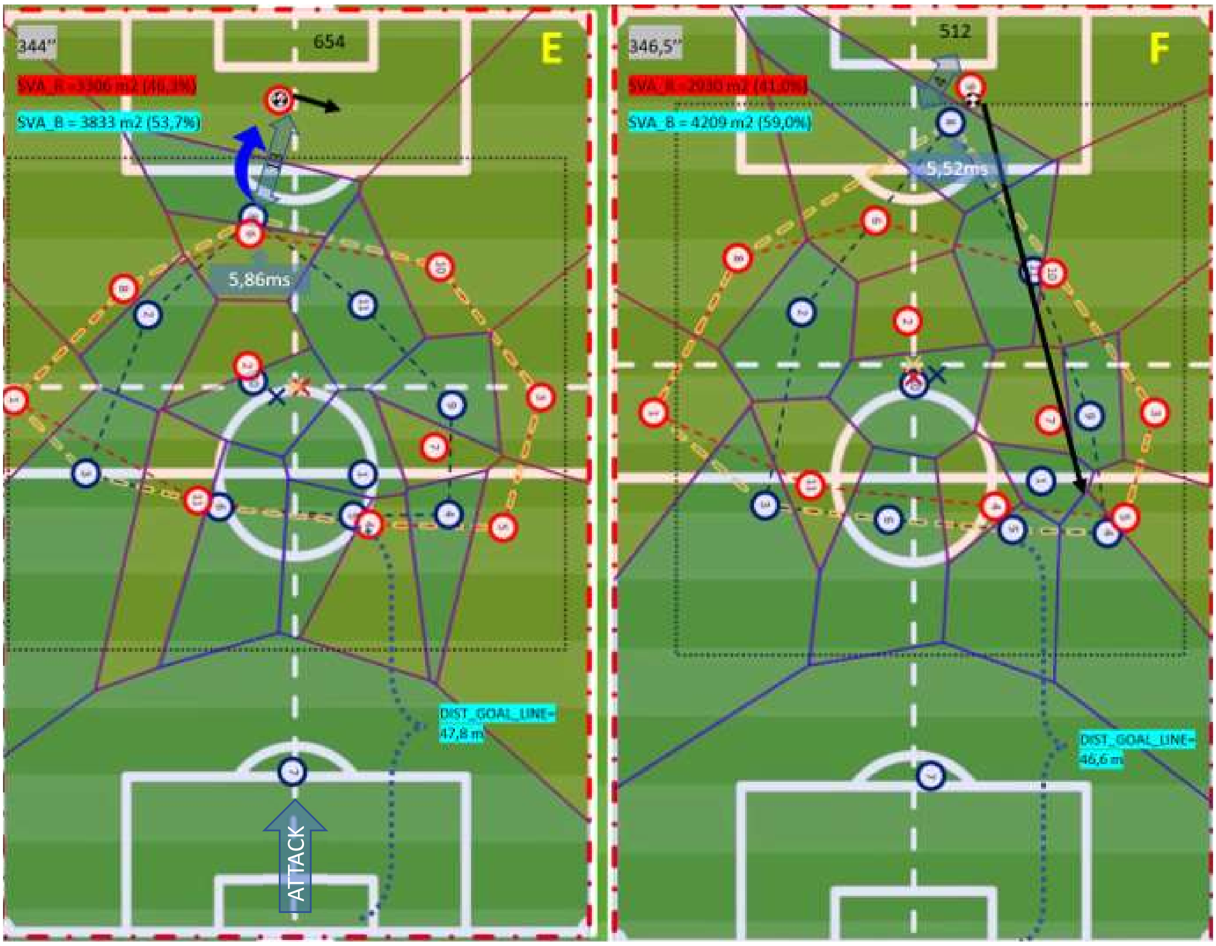



**Figure 9.3:** Continuity of a sequence of diagrams (E and F) of a collective high-press (blue team)

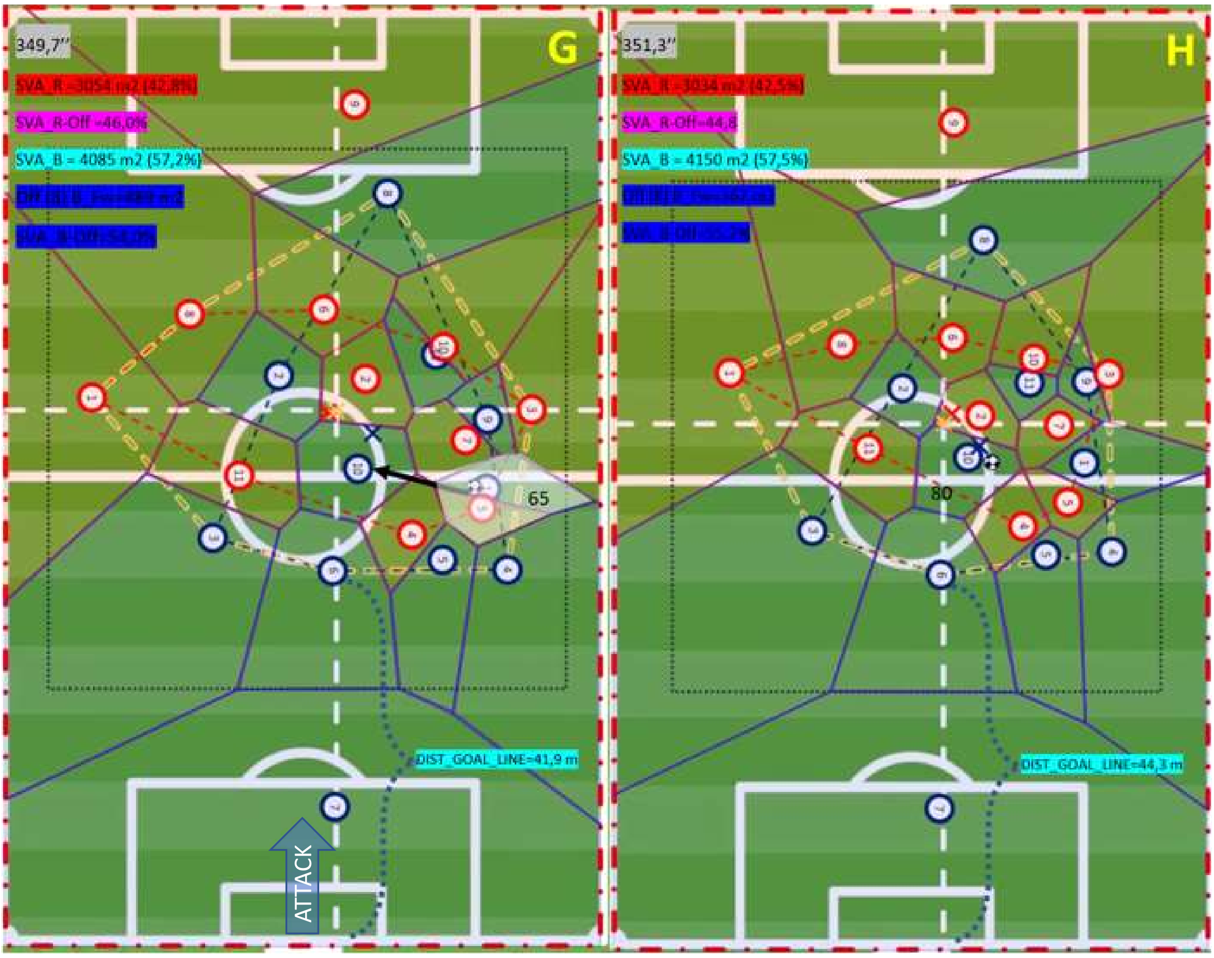



**Figure 9.4:** End of a sequence of diagrams (G and H) of a collective high-press (blue team)

Following this long pass, another important component of the game emerges: the duel! In fact, the territorial superiority achieved through the high press collective action lead the team in possession (red) to struggle in keeping the ball (quantified by the successive reduction of the individual Voronoi areas of the successive ball carriers). Moreover, the existence of more than $45 meters$ behind the back of the last defensive line leaves a huge potential risk to the blue team. It is exactly this risk that we can observe in diagram G (Figure 9.4), because if the duel was won by the no. 5 of the red team, this could mean a head deviation (flick) for his colleague (no. 4). This could lead to an enormous space to explore, i.e, the more than 40 meters that still exist on the back of the defensive line (which in the meantime retreated a little to cover the colleague who entered the duel). However, being faster in analysing the trajectory of the ball and anticipating his own displacement, in diagram H (Figure 9.4) we can observe how the no. 1 of the blue team managed to win the duel, passing the ball to his colleague (no. 10).

In sum, this set of diagrams of Figures 9.1 to 9.4 illustrates an excerpt of a possession episode 4 by the red team, exposing the importance of the blue team members (out of possession) to deal in a coordinated way with the risk/security. This is a difficult balance that underlies this tactical problem linked to the high press, insofar as it implies the consequence of increasing the area behind the defensive line. Therefore, the coordinated individual displacements of the players of the blue team, provided an evident territorial

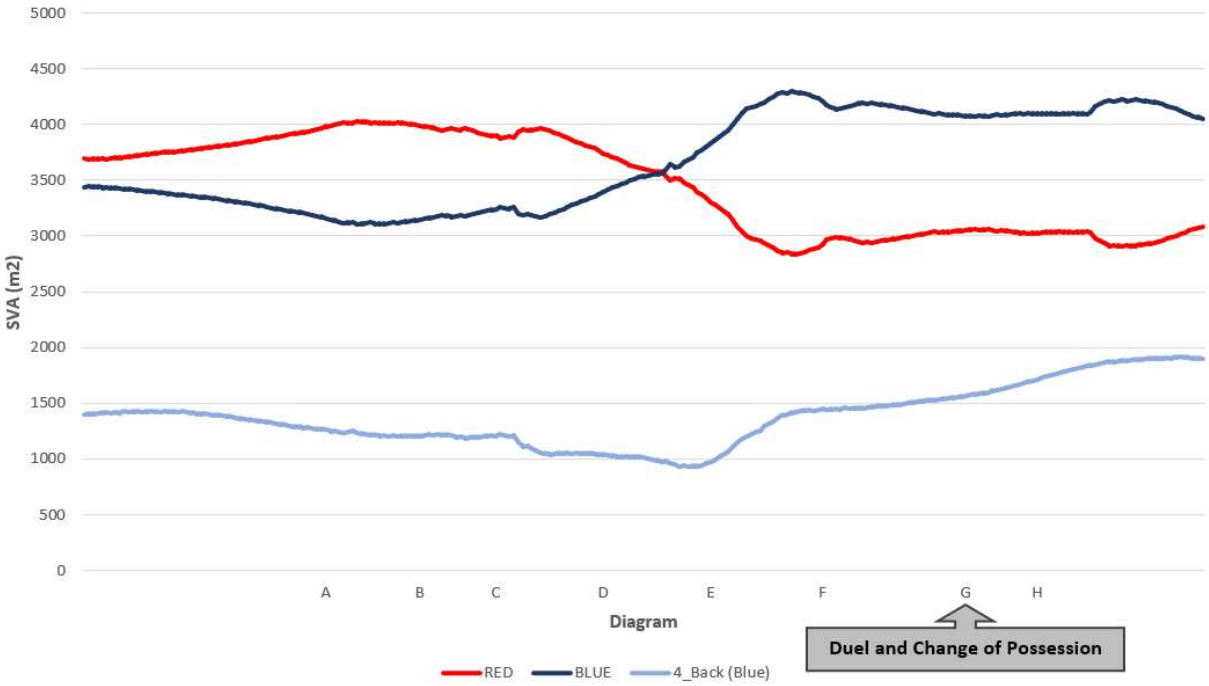



**Figure 9.5:** Variation of both teams SVA during the "possession episode" of Figures
*Note:* The "Sum of Voronoi Areas" (SVA) time-series of the two teams, highlighting the instants of the diagrams illustrated in Figure 9.1 to 9.4, with a 3rd line (light blue) representing the partial SVA of the four players of the defensive line (two "side backs" and two "central backs") of the blue team. 9.1 to 9.4

superiority, visible through the greater SVA, as can be observed in the graph of Figure 9.5. In this graph it is possible to observe how the blue team's *territorial dominance* long preceded the moment of recovery of possession of the ball, as well the decisive character of the duel. In fact, since a larger area of the team as a whole (SVA) also implied an increase in the Voronoi areas of the 4 elements of the defensive line (which means a greater area to protect and, therefore, an increased vulnerability to a break-up movement of a fast opponent).

It is based on these types of examples, that is possible to state that the phases of ball *in possession* and *out of possession* are not synonymous with *attack* and *defence*, and should be understood as distinct concepts 4. It is also because of this obvious practical application that we underline the interest of this variable (SVA). In conjunction with other indicators (e.g. distance to the nearest opponent and rate of decrease/increase of individual areas), can be used in the practice of coaches as a means of quantifying the effectiveness of collective synergies that are obtained by the *joint work* of the members of a team in a competitive environment (in this case at the level of high press actions).

## 9.3 An individual tactical dilemma of a central defender

In another example of how the Voronoi cell areas and some of its related metrics may be operationalized in order to create quantitative tools for evaluating the synergistic behaviour of football teams 7, we looking now for a type of tactical problem that is often present in the role of the players of the last defensive line. In fact, when a team is *out of possession*, players are still conditioned by their perception of the available spaces (for themselves but also for their opponents)(Silva et al., 2013), making choices about what is the best distance to maintain regarding the opponents. This is especially true in the case of a defender who decides to reduce the space for his direct opponent, even if that amplifies the space on his back. This is the case illustrated by the six diagrams of Figure 9.6, which began (A) with the ball in the blue team, namely in its Right Central Back (5). This player has ample space to pass forward to his colleague with the no. 9 (WR or Right Winger), who appears in a large enough interior space ($81m^2$) to receive the ball. At that moment ($matchtime = 299.7''$), the no. 11 (MO or Offensive Midfielder) who is also in the interior space, is moving diagonally and seems already attracting the attention of the opposing CBL (no.10 of the red team). This attraction is confirmed $1.3$ seconds later by diagram B of Figure 9.6, which corresponds to the moment when the WR passes the ball with only 1 touch to the MO, resulting in a strong movement of approximation of the CBL in order to reduce the reception space. However, due to the very short space available for the MO of the blue team (11) to control the ball (only $20m^2$), he chooses to return the ball again to the player who had passed him (diagram C of 9.6. When the ball is received again (only $9tenths$ of a second later), it is already evident the movement of the FW (no. 8) to take advantage of the space of the back of the CBL of the red team (no. 10), as is visible in diagram D.

In turn, seeing the movement of the FW (8) and the gradually increased space that it has available ($100m^2$) previewing a possible opportunity to shoot with high probability of success (i.e. with a high "Finishing Space Value" or FSV), the WR (9) makes the "assistance pass" 7. Thus, it is evident that, by choosing to reduce the space for an opponent who appears in front (11), the movement of reduction of the CBL on him, was a tactical resolution that left open the possibility of the opposing team (through the no. 8) to find a situation with a higher probability to score (see 7).

Of course, as we can see in diagram F (9.6), it is a very short time window, because $2tenths$ of a second later, still barely the ball had left the foot of no. 9, already the no. 8 (FW) of the blue team would meet himself beyond the opponent's defensive line and will be, therefore, in an offside situation.

In sum, with this example, we try to illustrate how the individual actions of both parties influence collective synergies at the level of a given team, in this case creating the conditions for the blue team to find the space to create an important opportunity to shoot with a high probability of success (see 7).

## 9.4 Conclusion

These two examples of tactical problems of the players of the team out of possession, when placed in this simplistic way may also seem to only merit uncomplicated answers. However, the fast pace of the high-level game implies the constant refresh of the players' perception and the consequent adaptation of their answers that are supported by their decision-making mechanisms to achieve a collective high degree of coordination (D. Araújo and Davids, 2016). In fact, is the evidence that the appropriate response in a given instant may no longer be in the following one, which justifies the investment made by the teams in improving the "degree of coordination" of their players' interactions, regarding the transience and instantaneity of the game landscapes. In this sense, the desire to truly help their players in achieve a

**Figure 9.6:** Sequence of diagrams (from A to F) illustrating the relevance of the "Voronoi area" as a metric to understand the tactical dilemma of a "central defender"

high degree of collective coordination (a strong synergistic effect), implies an empathic effort to coaches, to understand the *time and space* features of the situations experienced by their players. This *empathy* (Glatte, Heidingsfelder, and Brodack, 2017) is required to understand the all set of constraints perceived by players in the resolution of their tactical problems, as a fundamental first step of the coach's intervention. Because this is not an easy task, the role of being a coach implies a *raid* beyond the current frontiers of science, implying the accumulation of experience in function, in the construction of a certain *art* (Taha and Thomas, 2003). In this line, the described examples with the support of Voronoi diagrams-based tools, modestly contribute to illustrate how the science of sport can gradually expand its boundaries to support football coaches in their role and, consequently, those that effectively matter in the game – the players.

## References


Afonso, José, Júlio Garganta, and Isabel Mesquita (2012). "Decision-making in sports: The role of attention, anticipation and memory". In: *Revista Brasileira de Cineantropometria e Desempenho Humano* 14.5, pp. 592–601. DOI: 10.5007/1980-0037.2012v14n5p592.

Andrienko, Gennady et al. (2017). *Visual analysis of pressure in football*. Vol. 31. 6, pp. 1793–1839. DOI: 10.1007/s10618-017-0513-2.

Araújo, D. and K. Davids (2016). "Team synergies in sport: Theory and measures". In: *Frontiers in Psychology* 7.SEP, pp. 1–13. DOI: 10.3389/fpsyg.2016.01449Team.

Araújo, Duarte et al. (2016). "The micro-macro link in understanding sport tactical behaviours: Integrating information and action at different levels of system analysis in sport". In: *Movement and Sports Sciences - Science et Motricite* 89.3, pp. 53–63. DOI: 10.1051/sm/2015028.

Glatte, Hannah, Marie Heidingsfelder, and Franziska Brodack (2017). "Strategies for synergies. Working in interdisciplinary teams". In: *Design Journal* 20.sup1, S4721–S4725. DOI: 10.1080/14606925.2017.1352971.

Gréhaigne, J., P. Godbout, and Z. Zera (2011). "How the " rapport de forces " evolves in a soccer match : the dynamics of collective". In: *Rev. Psicol. Deporte* 20, pp. 747–765.

Gréhaigne, Jean Francis, Daniel Bouthier, and Bernard David (1997). "Dynamic-system analysis of opponent relationships in collective actions in soccer". In: *Journal of Sports Sciences* 15.2, pp. 137–149. DOI: 10.1080/026404197367416.

Hughes, Mike and Trevor Lovell (2019). "Transition to attack in elite soccer". In: *Journal of Human Sport and Exercise* 14.1, pp. 236–253. DOI: 10.14198/jhse.2019.141.20.

López-felip, Maurici A and Till D Frank (2017). "Synchronization Assessment for Collective Behavior". In: *CogSci*, pp. 706–710.

Low, Benedict, Gabriel Vilas Boas, et al. (2018). "Exploring the effects of deep-defending vs high-press on footballers' tactical behaviour, physical and physiological performance: A pilot study". In: *Motriz. Revista de Educacao Fisica* 24.2, pp. 1–7. DOI: 10.1590/S1980-6574201800020009.

Low, Benedict, Robert Rein, et al. (2021). "The porous high-press ? An experimental approach investigating tactical behaviours from two pressing strategies in football". In: *Journal of Sports Sciences* 39.19, pp. 2199–2210. DOI: 10.1080/02640414.2021.1925424.

Newell, K. (1986). "Constraints on the development of coordination". In: *Motor development in children. Aspects of coordination and control*. Ed. by MG Wade and HTA Whiting. Dordrecht: Martinus Nijhoff, pp. 341–360.

Oliveira, J. and F. Tavares (1996). *Estratégia e táctica nos jogos desportivos colectivos*. Universidade do Porto.

Power, Paul et al. (2017). ""Not all passes are created equal:" Objectively measuring the risk and reward of passes in soccer from tracking data". In: *Proceedings of the ACM SIGKDD International Conference on Knowledge Discovery and Data Mining* Part F1296, pp. 1605–1613. DOI: 10.1145/3097983.3098051.

Ribeiro, João et al. (Oct. 2019). “Exploiting Bi-Directional Self-Organizing Tendencies in Team Sports: The Role of the Game Model and Tactical Principles of Play”. In: *Frontiers in Psychology* 10. DOI: 10.3389/fpsyg.2019.02213.

Searle, John R. (1990). “Collective Intentions and Actions”. In: *Intentions in communication*. Ed. by P. Cohen, J. Morgan, and M. Pollack. Bradford Books, MIT Press, pp. 401–415. DOI: 10.1017/cbo9780511606366.007.

Silva, Pedro et al. (2013). “Shared knowledge or shared affordances? insights from an ecological dynamics approach to team coordination in sports”. In: *Sports Medicine* 43.9, pp. 765–772. DOI: 10.1007/s40279-013-0070-9.

Taha, T. and S. Thomas (2003). “Systems modelling of the relationship between training and performance”. In: *Sports Medicine* 33.14, pp. 1061–1073.

Taki, Tsuyoshi and Jun ichi Hasegawa (2000). “Visualization of dominant region in team games and its application to teamwork analysis”. In: *Proceedings of Computer Graphics International Conference, CGI*, pp. 227–235. DOI: 10.1109/cgi.2000.852338.

Wade, A. (1998). *Principles of team play*. Reedswain Inc..

# Chapter 10

# General discussion and future research

## 10.1 General discussion

Underpinned on the ecological dynamics' framework (Duarte Araújo, Keith Davids, and Hristovski, 2006; Keith Davids, Duarte Araújo, Correia, et al., 2013), this thesis is grounded in the main idea that the performer–environment relationship is the most relevant scale of analysis of football performance (Duarte Araújo, Travassos, and Vilar, 2010). As an invasion team sport (Teodorescu, 1984; Thorpe, Bunker, and Almond, 1986), each football player's action is embedded in their team's collective environment, which in turn is nested within the match competitive environment (Pol et al., 2020). In this context, players' ability to perceive *shared affordances* in the performance competitive environment (Silva, Garganta, et al., 2013) is crucial to the survival of the "fittest" teams (Passos, Duarte Araújo, and Keith Davids, 2016).

This rationale, very significant for all football coaches that every week struggle to "survive" on the job (Paola and Scoppa, 2012), is coherent with the "holistic Darwinism" theory (Corning, 2010), that we discussed in chapter 2 as a conceptual support for this thesis based in the literature review. This theory has its roots in the "synergism hypothesis" that situates cooperation as the main evolutionary impulse of nature (Corning, 1983). In this "hypothesis about how Nature handles biological complexity" (S. Kelso, 2009, p1537), the synergies (i.e, the "*functional effects that are jointly created and that are not otherwise attainable*" (Corning, 2018, ch2) are considered the main cause of life's evolution.

These ideas led us to focus throughout this thesis on *players' interactions* and the emergent synergies as possible containing relevant patterns to understand a football team's performance. Being a multi-level and hierarchical model of complex systems analysis, this Corning's paradigm (Corning, 1983; Corning, 2010; Corning, 2018) is confluent with the purpose of capturing the properties of team synergies through methods that go beyond the principles of the "Synergetics" (Haken, 1983). In fact, we considered that the measures of synchrony do not elucidate *per se* the functional effects emerging from players' interactions (López-felip and Frank, 2017), being important to choose other methods with the potential to test the properties of team synergies (D. Araújo and K. Davids, 2016).

Reviewing several different *reductionists* (e.g., dyads) and *holistic* approaches (e.g., team centroids) used to assess the interactions between football players and teams, we argue that some spatial measures are able to reconcile the two perspectives. Between them, the ones that allow capturing players' and teams' *space dominance* (Taki and Hasegawa, 2000), can respond to the challenge of the "synergism hypothesis" of reconciling the *reductionist* and the *holistic* approach to team performance's research. For this reason in chapter 3, supported by similar applications in other fields of knowledge, we argue that, from a spatial point of view, the functional effects that result from players' joint work (synergies) can be also captured by *Voronoi diagrams* (VD). In fact, we consider VD as a "*glocal*" (Robertson, 1995) tool, because behind this procedure there is a Delaunay tessellation that implies the connection of each point (player) with their nearest local neighbours. This *net* of distances and angles of every player with their neighbours draws, at the same time, a global picture of the entire match landscape (Chiu and Barnes, 2003).

With the support of these two conceptual chapters (2 and 3), the following four chapters of this thesis were composed of applied studies (4, 5, 6 and 7). These aimed to establish a link between a team's performance and the *functional effects* that emerge from players' interactions (Silva, Vilar, et al., 2016), revealing the inherent behavioural spatial *patterns* of these synergies. Using real matches events and positional data, these works were dedicated to exploring the properties of collective synergies, establishing a link between the *functional effects* that emerge from players' interactions and their payoffs (i.e., performance metrics).

In chapter 4, we argued that *territorial dominance* is key to the overall team's performance in high-level football. As an invasion collective game, a football team's territorial dominance only can be achieved by the coordinated effort of their players to occupy a pitch location that assures a certain "space dominance" (Taki and Hasegawa, 2000), regarding the ball position and the offensive and defensive goalposts. In this chapter 4, we hypothesized that if there is a clear link between ball possession *effectiveness* (creation of goal-scoring opportunities) and a team's *territorial dominance*, it can be equated as an expression of their *attacking intentionality* (Mateus, 2005; D. Araújo and K. Davids, 2016). This possibility was tested through the team's *convex hull* (CH) (Moura et al., 2012) and the team's "*Sum of Voronoi Areas*" (SVA)(Fonseca, Milho, Travassos, and Duarte Araújo, 2012). Our results confirmed previous studies (A. Lopes et al., 2013; António Lopes et al., 2015) indicating that the SVA is an adequate metric to assess the teams' *territorial dominance* during effective *possession episodes* (PE), being more precise than CH (Moura et al., 2012). Importantly, it was demonstrated that the SVA can be used to assess teams' effectiveness not only at the end of the PE but also during the "out of possession" phase, as the territorial dominance can start before the regain of the ball's control. This finding, clarify that "possession" and "attack" (as "out of possession" and "defence") are not overlapped concepts.

In chapter 5, we proposed and tested a method to establish a link between the team's configuration on the pitch and the ball carrier's passing affordances. The *functional effects* that emerge from players' distribution on the field in a given moment, influence the team's ability to maintain the ball possession. Thus, capturing the team's collective synergies into *functional degrees of freedom* (fDOF), our method *proof of concept* demonstrated how is possible to dynamically capture passing affordances (i.e., opportunities for players to interact through passing) from the players' positional quantitative data. Signifying a conceptual break in relation to static methods for analysing the distribution of players on the field (Brooks, Kerr, and Guttag, 2016; Garrido et al., 2020; Smith and Lyons, 2017), our method introduced more granularity and precision to already previously presented dynamic methods (Vilar, Duarte Araújo, Keith Davids, and Bar-Yam, 2013). In this chapter 5, we had the opportunity to exemplify how the method and the idea of teams' fDOF can be applied in different scenarios and time scales, combined with other contextual data to qualitatively substantiate the tactical knowledge of coaches on the performance of their teams.

The investigation of the chapter 6 was dedicated to understanding the influence of *team formation* (TF) and *players' roles* (PR) in their dynamic "combination of labour" synergies (Corning, 2010). This property of synergies also known as "interpersonal linkages", translates "the specific contribution of each element to a group task" (D. Araújo and K. Davids, 2016, p8), in this case from a spatio-temporal point of view. The detected behavioural patterns are crucial to understanding players' interactions and the resulting payoffs at a team level (e.g., maintaining ball possession or achieving territorial dominance over the opponent team). In this case, we used Voronoi diagrams to assess each player's "space dominance" (Taki and Hasegawa, 2000; Rein, 2016), considering the entire dynamic emerging from all players on the pitch, and not only based in a single team analysis (Santana, 2011; Fonseca, Milho, Travassos, Duarte Araújo, and António Lopes, 2013). Our results showed that TF and PR constrain their spatial interpersonal linkages, changing the available landscape of affordances. In fact, statistical differences were possible to establish greater proximity with PR of team formation classes or sectors (i.e., defenders, midfielders, forwards) and relative pitch location (interior or exterior in the effective playing space). Differences were also found between players with similar roles when in different team formations, which made it possible to underline the need for representative training given these constraints (TF and PR).

In the last applied study of this thesis (chapter 7), we argue that the ball carrier's decision-making about shooting or passing cannot be seen as an individual process, being a collective decision that emerges from the player's perception of the affordances in a game landscape. From our point of view, this perspective is an important improvement of expected goals models, which quantifies the probability to score only based on each player's location on the pitch, not considering their interactions (Eggels, 2016; Rathke, 2017; Spearman, 2018). We based our approach on the idea that are two main spatio-temporal questions that can express players' (shared) affordances perception: a) is the opponent's target successfully *reachable* from this point where I am (or where a given teammate is)? and, b) can I (or any teammate) shoot with *enough* space (low adversaries' interference)?

These typical affordances that players perceive near the opponent's goal, were the foundation stones of a model (*Finishing Space Value* or FSV) to quantify who can occupy the best location to shoot in a given spatio-temporal match landscape. This model to quantify the "best option" to finish the play, does not equate other constraints, such as, for example, the individual perception of the accuracy or power of the shot from a certain point on the pitch. It is then limited to capture only the opportunities for action that are possible to measure through positional data in two dimensions (in the pitch longitudinal and lateral axis). The usefulness of the FSV model was tested by comparing it with the subjective opinion of a panel of experts, proving its ability to quantify the affordances of the shooting circumstances for the ball carrier's decision-making (to shoot or to pass).

## 10.2 Practical implications and thesis limitations

Although here assuming a researcher role, it is not possible to separate ourselves from the concerns that are raised by our daily professional coaching practice. In fact, as this thesis arose from our concerns on the ground as coaches, we could not fail to reflect on the practical usefulness of its research content.

Thus, chapters 8 and 9 constitute a reflection from a coach's point of view, about how the tools of previous chapters can be applied to tactically interpret the game and players' collective decisions. Thus, variables such as the "Sum of Voronoi Areas" (chapter 4) and the parameters used in the "Finishing Space Value" model (chapter 7), or the "functional degrees of freedom" methodology (chapter 5), were used here to exemplify how the coach's analysis of some tactical problems can benefit from these quantification methods. These examples, focusing on the team "*in possession*" in chapter 8 and *out of possession* in chapter 9, allow an approximation to quantify some spatial parameters related to players' "space dominance" and teams' collective "territorial dominance". We seek to demonstrate that these tools, due to their usefulness in quantifying the affordances potentially perceived by players and the synergies that emerge from their interactions, allow for an eminently coaches' qualitative tactical interpretation.

The reflections of these last chapters 8 and 9 were a possible way to bridge the gap between theory and practice. However, we would like to summarize here the potential practical implications of this thesis for football coaches' practice.

This thesis first contributes to coaches' practice at two main conceptual levels. In the first place, the idea that the survival of the *fittest* team relies on its collective performance (Passos, Duarte Araújo, and Keith Davids, 2016). It is an emergent consequence of players' ability to perceive the affordances that persistently arise in competitive match environments (Renshaw et al., 2019), guiding the players' interactions and the establishment of synergies (D. Araújo and K. Davids, 2016). Consequently, more than a training process-oriented toward the development of each player's individual capacities (e.g., physical condition), football training should be oriented to the collective adaptation of players' interactive behaviour in competition. Moreover, instead of prescribing solutions that stereotype players' interactions, coaches' intervention should be oriented to provide a training environment that assures a *behavioural correspondence* (Duarte Araújo, Keith Davids, and Passos, 2005; Duarte Araújo, Hristovski, et al., 2019) with the non-linear, variable and unpredictable competitive environment (Mateus, 2005; Duarte et al., 2013; Woods et al., 2020). In the second place, from a football coach's point of view, the team's overall performance (match result or league ranking) is essentially dependent on the functional effects that emerge from players' interactions, i.e., their synergies (Pol et al., 2020). This evidence underlines the importance that football coaches attribute to the tactical side of performance (Garganta, 2009; Tamarit, 2013). As these "functional effects" can have a positive, negative or neutral payoff (performance) (Corning, 2010), is essential to establish a link between the synergies and players' interactive behavioural patterns (D. Araújo and K. Davids, 2016). Consequently, match analysis and performance sports sciences departments should be oriented to refuse explanations of team performance as only directly dependent on individual actions and performance (Dellal et al., 2011; Duch, Waitzman, and Nunes Amaral, 2010). As mentioned, football is clearly an interactive non-linear and complex sport (Keith Davids, Duarte Araújo, and Shuttleworth, 2005), making little sense to overestimate individual performance without understanding collective interactions, as, on the contrary, to think that collective performance does not depend on individual actions and performance.

That's why we support the "synergism hypothesis" and the view that the functioning of the parts influences the behaviour of the whole, just as the whole influences the behaviour of the parts (Corning, 2018).

Moreover, match analysis departments' activities should not be limited to detecting the behavioural patterns emerging from players' interactions in competition (own teams and opponents), but also to understanding the *behavioural correspondence* with their training environments. In fact, match analysis departments should be an essential resource for coaches' constraints manipulation of representative training tasks (Práxedes et al., 2018). Currently, at a high level, football clubs have the human and material resources that allow them to be on the cutting edge of applied research in football. For example, the quantitative data that clubs collect, both in training and competition environments, is enormous and can contribute to a significant advance in the characterization of representative training exercises. Here we were limited to data extracted from real matches (competition), and it was not possible to establish the desired link with the training environment. However, in all applied studies, we assumed that through the patterns emerging from players' interactions in competition and the functional effects that derive from them (synergies), we would be contributing to a greater understanding of high-performance football in general terms. As detailed in chapters 4 and 5, the findings around the "territorial dominance", of teams and players, are particularly relevant for match analysis purposes and also to support coaches in the design and monitoring of "representative training tasks" (Pinder et al., 2011; Travassos et al., 2012; Vilar, Duarte Araújo, Keith Davids, and Renshaw, 2012). On the other hand, even if based on small databases, the proposed methods of chapters 5 and 7 to assess, respectively, teams' collective "functional degrees of freedom" (fDOF) and players' "finishing space value" (FSV) in shooting situations, can pave the way to the development of new tools to support coaches' intervention. In an integrated way, it was confirmed the utility of quantitative tools based on Voronoi diagrams to the assessment of players' interactive behaviour and the inherent emergent functional effects (synergies).
Future research could continue to improve these metrics, but essentially in establishing a link between the competitive and the training environments, investigating the impact of constraints manipulation on the design of training exercises. As defended above, it is essential for the cooperation between coaches and the different club departments (match and performance analysis, data and sport science, etc.) to consolidate the knowledge about football performance in each club's reality. Each coach has his/her philosophy, game model and training principles, being difficult to "speculate" about the team's performance without being aware of these crucial constraints. Consequently, the cooperation between clubs and the academic community is also essential to progress in football teams' performance general knowledge.
The functional effects resulting from players' cooperation (i.e., the synergies) are always decisive to evolution and will be not different in the football context (J. S. Kelso, 2017). So far, the synergies between clubs and the academic community are only occasional. Possibly due to constraints on both sides (e.g., the fear of sharing data that could take away some competitive advantage), but they have to be blurred in the near future to advance knowledge that will be potentially beneficial to all.

## 10.3 Future research

After this journey, we must humbly realize that the contributions possibly extracted from this thesis are small and much remains to be done in the research on functional synergies in high-performance football teams.

However, the conceptual framework used and the proven potential of the proposed metrics to assess collective and individual "space dominance" (as extracted from Voronoi diagrams), can pave the way for important future contributions. As a measure of an eminently "glocal" character to assess the interactions between players, Voronoi diagrams-based measures have the potential to capture the game's dynamic from a spatio-temporal perspective.

From our point of view, the measurement of players' "space dominance" is a coherent approach to potentially perceived spatial affordances. For example, free spaces around players are more indicative of passing action possibilities than imaginary lines connecting players. In fact, high-level players explore space in its three dimensions and, even if there is an obstacle on the surface plane, they will be able to pass the ball to a teammate if they wish to do so (e.g., making the ball pass over their closest opponent's supporting foot). With this example, we defend the idea that the spaces around the ball carrier, as well as around the player to whom he/she intends to pass, are essential affordances that guide passing actions. However, even if Voronoi-diagrams-based metrics in 2D are more discriminative of players' affordances than simple distances and angles between two players, these ideas can be already improved with the availability of 3D data of real matches. Thus, using Voronoi diagrams-based models with 3D data (Croci et al., 2020) represents a huge challenge for the quantification of players' interactive opportunities for action (affordances), for example, concerning dribbling, passing or shooting interactions. Nevertheless, even remaining in 2D positional data, some other clues for future research emerged from our applied works. In fact, Voronoi diagrams (VD), like other more complex spatial measurements based on the idea of dominant regions (Taki and Hasegawa, 2000), should be seen as a broad-spectrum tool with the ability to explore team's synergies properties (D. Araújo and K. Davids, 2016). Beyond all the studies that investigate the behavioural correspondence between the training and competitive environment (level of representativeness), VD can allow answering questions such as:

- In a more global dimension, as addressed in chapter 4, could the *Sum of Voronoi Areas* (SVA) that expresses teams' territorial dominance, be a consequence of the team's composition (i.e., the specific set of individuals selected to form a team to a specific match)? Or it will be possible to identify a sort of leadership process (Reebs, 2000; Passos, Duarte Araújo, and Keith Davids, 2013) associated with teams' territorial dominance? Another important question that links the micro and the macro (Duarte Araújo, Passos, et al., 2016) regards the relationship between a team's territorial dominance (SVA) and players' energy cost. In other words, can be possible to establish a link between the SVA and some variables related to players' individual physical effort (such as the meters at different intensities or their physiological impact)?

- An important question that results from our proposal in chapter 5, is related to the need to understand if, in fact, a team's *functional degrees of freedom* (fDOF) influence the *success* of the episodes of possession (e.g., the creation of opportunities to shoot)? If yes, it is important to understand the circumstances where fDOF could be related to teams' effectiveness (e.g., during the building-up phase).

- Regarding chapter 6, is important to clarify if players' individual space dominance, related to team formations (TF) and players' role (TF), is dependent on the degree of players' specialization on that PR. For example, if the typical Voronoi areas of players who are experts in a given PR (which usually perform it) are distinct from those who perform it circumstantially (e.g. when a colleague is injured)?
- About the Finishing Space Value (FSV) proposal (chapter 7), is important to clarify the link between this variable and play outcomes (e.g., scoring). On the other hand, having only evaluated the perception of the coaches (panel of experts) to test the FSV proposal, would the results go in the same line if the comparative instrument was also based on the declaration of players' perception?

These are some examples of research questions that the suggested methods and tools can seek to answer in future works to continue testing the "synergism hypothesis" and to understand the football teams' performance. In all of them, there is an evident preoccupation to approach the problems and the language used by the coaches. In fact, it is crucial to maintain a qualitative character behind any quantitative research, in the continuous search for a certain "*quantilification*" of this beautiful game that can be used by coaches and other practitioners in their practice.

## References


Araújo, D. and K. Davids (2016). "Team synergies in sport: Theory and measures". In: *Frontiers in Psychology* 7.SEP, pp. 1–13. DOI: 10.3389/fpsyg.2016.01449Team.

Araújo, Duarte, Keith Davids, and Robert Hristovski (2006). "The ecological dynamics of decision making in sport". In: *Psychology of Sport and Exercise* 7.6, pp. 653–676. DOI: 10.1016/j.psychsport.2006.07.002.

Araújo, Duarte, Keith Davids, and Pedro Passos (2005). "Ecological Validity, Representative Design and Correspondence between Experimental Task Constraints and Behavioral Settings Comment on Rogers, Kadar and Costall (2005)". In: *Ecological Psychology* 19.1, pp. 69–78.

Araújo, Duarte, Robert Hristovski, et al. (2019). "Ecological cognition: expert decision-making behaviour in sport". In: *International Review of Sport and Exercise Psychology* 12.1, pp. 1–25. DOI: 10.1080/1750984X.2017.1349826.

Araújo, Duarte, Pedro Passos, et al. (2016). "The micro-macro link in understanding sport tactical behaviours: Integrating information and action at different levels of system analysis in sport". In: *Movement and Sports Sciences - Science et Motricite* 89.3, pp. 53–63. DOI: 10.1051/sm/2015028.

Araújo, Duarte, Bruno Travassos, and Luís Vilar (2010). "Improving decision making skill in soccer". In: *Perceptual and motor skills* 110.3, pp. 1086–1088. DOI: 10.2466/05.07.25.28.PMS.110.C.1086-1088.

Brooks, Joel, Matthew Kerr, and John Guttag (2016). "Developing a data-driven player ranking in soccer using predictive model weights". In: *Proceedings of the ACM SIGKDD International Conference on Knowledge Discovery and Data Mining* 13-17-Augu, pp. 49–55. DOI: 10.1145/2939672.2939695.

Chiu, Loren Z.F. and Jacque L. Barnes (2003). "The Fitness-Fatigue Model Revisited: Implications for Planning Short- and Long-Term Training". In: *Strength and Conditioning Journal* 25.6, pp. 42–51. DOI: 10.1519/1533-4295(2003)025<0042:tfmrif>2.0.co;2.

Corning, Peter (1983). *The Synergism Hypothesis: A Theory of Progressive Evolution*. McGraw-Hill, New York.

— (2010). *Holistic Darwinism*. University of Chicago Press.

— (2018). *Synergistic Selection: How Cooperation Has Shaped Evolution And The Rise Of Humankind*. WORLD SCIENTIFIC PUBLISHING CO PTE LTD.

Croci, Simone et al. (2020). "Visual attention-aware quality estimation framework for omnidirectional video using spherical Voronoi diagram". In: *Quality and User Experience* 5.1. DOI: 10.1007/s41233-020-00032-3.

Davids, Keith, Duarte Araújo, Vanda Correia, et al. (2013). "How small-sided and conditioned games enhance acquisition of movement and decision-making skills". In: *Exercise and Sport Sciences Reviews* 41.3, pp. 154–161. DOI: 10.1097/JES.0b013e318292f3ec.

Davids, Keith, Duarte Araújo, and Rick Shuttleworth (2005). "Applications of Dynamical Systems Theory to Football". In: *Science and Football V: The Proceedings of the Fifth World Congress on Science and Football* i, pp. 537–550.

Dellal, Alexandre et al. (2011). "Comparison of physical and technical performance in European soccer match-play: Fa Premier League and La Liga". In: *European Journal of Sport Science* 11.1, pp. 51–59. DOI: 10.1080/17461391.2010.481334.

Duarte, Ricardo et al. (2013). "Competing together: Assessing the dynamics of team-team and player-team synchrony in professional association football". In: *Human Movement Science* 32.4, pp. 555–566. DOI: 10.1016/j.humov.2013.01.011.

Duch, Jordi, Joshua S. Waitzman, and Luís A. Nunes Amaral (2010). "Quantifying the performance of individual players in a team activity". In: *PLoS ONE* 5.6, pp. 1–8. DOI: 10.1371/journal.pone.0010937.

Eggels, H. (2016). "Expected Goals in Soccer: Explaining Match Results using Predictive Analytics". PhD thesis.

Fonseca, Sofia, João Milho, Bruno Travassos, and Duarte Araújo (2012). "Spatial dynamics of team sports exposed by Voronoi diagrams". In: *Human Movement Science* 31.6, pp. 1652–1659. DOI: 10.1016/j.humov.2012.04.006.

Fonseca, Sofia, João Milho, Bruno Travassos, Duarte Araújo, and António Lopes (2013). "Measuring spatial interaction behavior in team sports using superimposed Voronoi diagrams". In: *International Journal of Performance Analysis in Sport* 13.1, pp. 179–189. DOI: 10.1080/24748668.2013.11868640.

Garganta, Júlio (2009). "Trends of tactical performance analysis in team sports: bridging the gap between research, training and competition." In: *Revista Portuguesa de Ciências do Desporto* 9.1, pp. 81–89.

Garrido, D. et al. (2020). "Consistency and identifiability of football teams: a network science perspective". In: *Scientific Reports* 10.1, pp. 1–10. DOI: 10.1038/s41598-020-76835-3.

Haken, Hermann (1983). *Synergetics: An Introduction*. Springer-Verlag. DOI: 10.1007/978-3-642-88340-8.

Kelso, JA Scott (2017). "Principles of Coordination: Synergies of Synergies!" In: *Complex Systems in Sport, International Congress. Linking Theory and Practice*. Ed. by Carlota Torrents, Pedro Passos, and Francesc Cos, pp. 13–16.

Kelso, Scott (2009). "Coordination Dynamics". In: *Encyclopedia of Complexity and Systems Science*. Ed. by R. Meyers. Springer, pp. 1537–1567. DOI: 10.1007/978-3-642-27737-5.

Lopes, A. et al. (2013). "Tracking Multiple Handball Players using Multi-Commodity Network Flow for Assessing Tactical Behavior". In: *Scientific Conference Women and Handball: Scientific and Practical Approaches*.

Lopes, António et al. (2015). "Using Voronoi diagrams to describe tactical behaviour in invasive team sports: An application in basketball". In: *Cuadernos de Psicologia del Deporte* 15.1, pp. 123–130. DOI: 10.4321/S1578-84232015000100012.

López-felip, Maurici A and Till D Frank (2017). "Synchronization Assessment for Collective Behavior". In: *CogSci*, pp. 706–710.

Mateus, J. (2005). "In pursuit of an ecological and fractal approach to soccer coaching". In: *Science and Football V : The Proceedings of the Fifth World Congress on Science and Football,* pp. 561–573.

Moura, Felipe Arruda et al. (2012). "Quantitative analysis of Brazilian football players' organisation on the pitch". In: *Sports Biomechanics* 11.1, pp. 85–96. DOI: 10.1080/14763141.2011.637123.

Paola, M. D. and V. Scoppa (2012). “The effects of managerial turnover: Evidence from coach dismissals in Italian soccer teams”. In: *Journal of Sports Economics* 13.2, pp. 152–168.

Passos, Pedro, Duarte Araújo, and Keith Davids (2013). “Self-organization processes in field-invasion team sports implications for leadership”. In: *Sports Medicine* 43.1, pp. 1–7. DOI: 10.1007/s40279-012-0001-1.

— (2016). “Competitiveness and the process of co-adaptation in team sport performance”. In: *Frontiers in Psychology* 7.OCT, pp. 1–5. DOI: 10.3389/fpsyg.2016.01562.

Pinder, Ross A. et al. (2011). “Representative learning design and functionality of research and practice in sport”. In: *Journal of Sport and Exercise Psychology* 33.1, pp. 146–155. DOI: 10.1123/jsep.33.1.146.

Pol, Rafel et al. (2020). “Training or Synergizing? Complex Systems Principles Change the Understanding of Sport Processes”. In: *Sports Medicine - Open* 6.1. DOI: 10.1186/s40798-020-00256-9.

Práxedes, Alba et al. (Jan. 2018). “The effect of small-sided games with different levels of opposition on the tactical behaviour of young footballers with different levels of sport expertise”. In: *PLoS ONE* 13.1. DOI: 10.1371/journal.pone.0190157.

Rathke, Alex (2017). “An examination of expected goals and shot efficiency in soccer”. PhD thesis. DOI: 10.14198/jhse.2017.12.proc2.05.

Reebs, Stephan G. (2000). “Can a minority of informed leaders determine the foraging movements of a fish shoal?” In: *Animal Behaviour* 59.2, pp. 403–409. DOI: 10.1006/anbe.1999.1314.

Rein, Robert (2016). “Measuring interpersonal coordination – a selection of modern analysis techniques”. In: *Interpersonal Coordination and Performance in Social Systems*. Routledge, Ch. 19 ( 295–311).

Renshaw, Ian et al. (2019). “Evaluating Weaknesses of “Perceptual-Cognitive Training” and “Brain Training” Methods in Sport: An Ecological Dynamics Critique”. In: *Frontiers in Psychology* 9, p. 2468. DOI: 10.3389/FPSYG.2018.02468.

Robertson, R. (1995). “Glocalization: Time-space and homogeneity-heterogeneity”. In: *Global modernities* 2.1, pp. 25–44.

Santana, Juliana (2011). “Representação da área de responsabilidade de jogadores de futebol através do Diagrama de Voronoi”. PhD thesis. Universidade Estadual de Campinas.

Silva, Pedro, Júlio Garganta, et al. (2013). “Shared knowledge or shared affordances? insights from an ecological dynamics approach to team coordination in sports”. In: *Sports Medicine* 43.9, pp. 765–772. DOI: 10.1007/s40279-013-0070-9.

Silva, Pedro, Luís Vilar, et al. (2016). “Sports teams as complex adaptive systems: manipulating player numbers shapes behaviours during football small sided games”. In: *Springerplus* 5.Heim 1958, p. 191. DOI: 10.1186/s40064.

Smith, Ronald A. and Keith Lyons (2017). “A strategic analysis of goals scored in open play in four FIFA world cup football championships between 2002 and 2014”. In: *International Journal of Sports Science and Coaching* 12.3, pp. 398–403. DOI: 10.1177/1747954117710516.

Spearman, William (2018). “Beyond Expected Goals”. PhD thesis, pp. 1–17.

Taki, Tsuyoshi and Jun ichi Hasegawa (2000). “Visualization of dominant region in team games and its application to teamwork analysis”. In: *Proceedings of Computer Graphics International Conference, CGI*, pp. 227–235. DOI: 10.1109/cgi.2000.852338.

Tamarit, Xavier (2013). *Periodización táctica vs Periodización táctica*. València: MB football.

Teodorescu, L. (1984). *Problemas de teoria e metodologia nos jogos desportivos*. Ed. by Ed. Horizonte. Lisboa.

Thorpe, R., D. Bunker, and L. Almond (1986). *Rethinking games teaching*. Department of Physical Education and Sport Science. Loughborough : University of technology.

Travassos, Bruno et al. (2012). “Practice task design in team sports: Representativeness enhanced by increasing opportunities for action”. In: *Journal of Sports Sciences* 30.13, pp. 1447–1454. DOI: 10.1080/02640414.2012.712716.

Vilar, Luís, Duarte Araújo, Keith Davids, and Yaneer Bar-Yam (2013). “Science of winning soccer: Emergent pattern-forming dynamics in association football”. In: *Journal of Systems Science and Complexity* 26.1, pp. 73–84. DOI: 10.1007/s11424-013-2286-z.

Vilar, Luís, Duarte Araújo, Keith Davids, and Ian Renshaw (2012). “The need for ’representative task design’ in evaluating efficacy of skills tests in sport: A comment on Russell, Benton and Kingsley (2010)”. In: *Journal of Sports Sciences* 30.16, pp. 1727–1730. DOI: 10.1080/02640414.2012.679674.

Woods, Carl T. et al. (2020). “Sport Practitioners as Sport Ecology Designers: How Ecological Dynamics Has Progressively Changed Perceptions of Skill “Acquisition” in the Sporting Habitat”. In: *Frontiers in Psychology* 11.April, pp. 1–15. DOI: 10.3389/fpsyg.2020.00654.