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Axiomatic Design Applied to Play Calling in American Football

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Abstract

The objective of this paper is to learn if the use of functional metrics and the use of parent-child equations can guide design decompositions for winning games. This study is performed in the context of designing play calling strategies in American football. The top level functional metric for FR0, outscore your opponent, is "point differential", which is controlled through the child metrics that comprise it. Using an on-line game simulator based on statistics from the 2015 season, in over 96 simulated games, two design solutions are tested statistically against last year's results in the National Football League (NFL). The results show that the solutions based on the application of functional metrics increase the number of wins compared with the actual results from 2015. This suggests that whatever system the NFL coaches were using in 2015 was not the best for winning.

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1. Introduction

American football provides an interesting opportunity to test the use of axiomatic design to create a game strategy. It is a highly structured game composed of a series of short precisely predefined and well-rehearsed "plays" where each player has a specific task. In between these plays the players and coaches can consult on the next play to call. The players line up in special formations before each play. Play calling strategies are designed here and tested in game simulations.

This work tests the utility of functional metrics (FMs) and the use of parent-child equations for guiding the decomposition of a design for winning games. The hypothesis is that controlling appropriate FMs can increase the likelihood that a team can outscore their opponent. The scope of this paper is designing play calling in American football games. In a more general sense it is applicable to other games and situations that rely on scores to determine success. For more on scoring and ball control in American Football see Appendix 1.

Metrics here are used to determine the degree of success of a system or process. An FM indicates how well a functional requirement (FR) satisfies a customer need (CN). Parent FMs relate to their children through parent-child equations that are expressed between all levels of the decomposition hierarchies. Upper-level FMs can be considered dependent variables, and the children FMs are the independent variables that combine to equal parent FMs [1].

FMs can be important for several reasons. Having FMs at every level can facilitate a decomposition that satisfies axiom one by being collectively exhaustive mutually exclusive (CEME) [2]. CEME means that the children are collectively exhaustive with respect to the parent and mutually exclusive with respect to each other. CEME applies to decompositions in all domains. Having an FM and a parent-child equation for each FR and design parameter (DP) provides a quantitative path for the determining children FR-DP pairs.

Without being able to quantify a system's current state, it cannot be objectively determined whether the system is improving or the amount of improvement [1].

When the system is underperforming, it can be difficult to trace the cause without FMs [3]. An evolving design solution must be able to identify and adjust underperforming elements within the solution. FMs at every level can facilitate

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identification and adjustment of underperforming elements.

NFL (National Football League) teams currently invest resources apparently to prioritize metrics that are not the best indicators for winning games. Certain positions on the field are considered more important for achieving certain metrics and can be given a larger percentage of the salary allotment, which is capped by the league.

There can be times when internal or external factors cause certain FMs within the design solution to no longer be as beneficial. This might be a result of reaching maximum capability or because the opponent has made an adjustment that your design solution is not well adapted to handle. A regular review and possible alteration of the design solution can prevent obsoletion of the design solution.

The techniques for the development of strategies and tactics for play calling in American football might also be applied to developing strategies and tactics for other sports and for business and government or military applications as well.

1.1. State of the Art

Due to the competitive manufacturing environment of the 1980s, organizations began investing effort into developing performance measurement systems that measured the effectiveness of the organization’s processes [4]. The performance-measurement record sheet [5] provides a list of criteria that must be present for a metric before it can be considered actionable.

Lewis [6] writes about the failure within US Major League Baseball to identify the right metrics. The 2002 Oakland Athletics were able to win the most games of any team in the league during the regular season, despite paying the third lowest salary to their roster by prioritizing metrics that correlate more strongly with wins.

Decision-making in football has been analysed based on the expected point value (EPV) [7, 8]. The EPV is based largely on the position on the field and is in fact the amount of points a team should be expected to score on average by having a first down at the current field position. This was developed by Carter et al. [7] by analysing data from the 1969 NFL regular season. With an EPV of 0 at one’s own 20 yard line, EPV increases roughly 1 point per 18 yards and can also be valued negatively, with a value of -1.25 at one’s own 5 yard line [9]. A common theme in the literature is that decision-makers for most teams during a game tend to be risk-averse in 4^{th} down situations, to the point of reducing their chance to win. This is due to making play calling decisions that reduce to total EPV over the course of the game [7, 8].

Suh [10] gives many examples of decompositions with metrics for the FRs and DPs. He proposed that ROI (return on investment) can be decomposed to three main FRs: (1) increase sales revenue, (2) minimize cost and (3) minimize investment. His design decomposes the FM equation for FR 0, ROI = (Sales-Cost/Investment). The next level of FRs and DPs are used to control each variable in the equation independently. Manufacturing System Design Decomposition (MSDD) was similarly designed using the same 3 three top level FRs as Suh [10] to satisfy the goal of maximizing return on investment [11]. Collective System Design is a method based on axiomatic design (AD) theory [12]. This system provides a behaviour and process for collective agreement during a company's conversion to lean, to achieve long term sustainability. This includes assigning metrics to FRs and DPs.

An initial design solution can adapt through a regular review and adjustment of the FMs to ensure that the design solution continues to be valuable. This kind of adapting design solution can save an organization the expense of having to develop a new performance measurement system [13]. The performance paradox model [14] explains the inevitable need for evolution as a requirement in every performance measurement system. A new set of metrics will need to be defined that measure the same value to the customer if the success rate of current solution becomes stagnant or moves in an undesired direction.

According to Cochran et al. [12] there are three options when the FMs are not acceptable:

(1) Improve the standard work without changing the physical solution (PS)

(2) Determine a new PS

(3) Change the respective FR.

1.2. Approach used here compared to the state-of-the-art

Similar to Suh [10] and Cochran et al. [11], AD is used here as the framework for the two design solutions, initial and adapting. However, unlike those authors, but similar to Henley [1], they will feature FMs and parent-child equations at every level. Similar to Brown [2], this design is an attempt at a CEME solution. Unlike his work, FMs and parent-child equations are used as a quantitative method for determining CEME. Similar to Bruns [4], Suh [10] and Cochran et al. [11], ROI is a top level FM for success. However, in this situation the return will be measured in points. Similar to Neely [5], the performance record sheet is used to determine actionable lower level FMs that control the top level FM. Similar to Lewis [6], the play calling strategies in this work will prioritize controlling lower level performance related FMs.

The play calling strategies here are intended to maximize the EPV in each game and in each series of plays and minimize the opponent’s EPV. Similar to Carter et al. [7] and Urschel et al. [8] decisions on 4^{th} down will be made to increase the EPV as opposed to a more risk adverse strategy that tends to favor punting and field goal attempts.

Also, similar to Cochran et al. [12] and Kennerley and Neely [13], the design solution must be able to be altered when it is underperforming. Similar to Cochran et al. [12], the method for addressing an underperforming FM is to first improve the standard work. One example situation might be controlling the metric for the time it takes to rush the quarterback. Improving the standard work could be changing out a player for one who is faster and therefore rushes the quarterback faster. If improving the standard work is not sufficient, the next option is to alter the DP. An example of this could be changing to a play that increases the number of players rushing the quarterback.

Unlike Cochran et al. [12] who suggests the possibility of defining new FRs as a possibility for improving performance, new FRs are not considered over the course of testing these design solutions. Unlike Meyer and Gupta [14], who suggest the possibility of defining new metrics as a possibility for improving performance, new metrics are not considered over the course of testing these design solutions.

2. Methods

2.1. Formulating two solutions

Fig. 1 shows the top two levels for the first design solution and FM equations for the third level. Both solutions are designed using axiomatic design and have the same FR0, FM0 and parent-child equations. The difference is that for the second design solution, DP0 is “Adaptive play calling strategy.”

The FR is defined to control the related FM, in this case FR0 is outscore your opponent and FM0 is point differential (PD).

The DPs define the scope of the design of the FRs and DPs at the lower levels, i.e., constrains them [15].

Each FM’s parent-child equation determines the next level of the decomposition [1]. Each lower level FM is a variable in the corresponding parent-child equation. FM 0 and its related parent-child equation are shown in Fig. 1.

PD depends on PSF and PSA. To control PD the user must control the two variables PSF and PSA. Thus there must be two FM-FR-DP sets at the next level, one to control PSF and the other to control PSA. As the solution for controlling the FM is not obvious, the FMs must then have their own children and parent-child equations to determine which lower FMs they are dependent on. This cycle is repeated until the solution for controlling the lowest level FMs is obvious. Sometimes the variables in the related equations are known but the exact formula for their combination is unknown. FM 1.2 is an example of that situation. Controlling the number of offensive possessions is a function of controlling the number of interceptions and fumbles in favor of the user’s team. However, the exact form of the equation might not be known. The full decomposition, with the FMs, extends for five levels.

In the adapting design solution each FM has a time derivative to indicate when the design solution requires evolution.

If the derivative over time of any of the FMs stagnates or trends in an undesirable direction, changes to improve the standard work are made. If this does not solve the problem then a new DP is chosen.

2.2. Testing the solutions

An online, comprehensive, statistic-based game simulator called *Action! PC Football* [16] was used to test the play calling strategies. This simulator mimics the performance of each team and their opponents from the selected season. The users call the plays and substitutes players. The statistics from the selected year are used to calculate results of each play called.

Three NFL teams were selected to represent the top, middle and bottom of the results from the actual season. The 2015 season was simulated for each of the selected teams, once with the fixed and once with the adaptive play calling strategy solution.

In both fixed and adaptive solutions the play calling choices are made to maximize the EPV of each series. EPV is FM 1.1, and is controlled by controlling the number of first downs and starting position of each series. Each play is chosen to consistently increase the EPV of that current series. Each position on the field has a specific EPV. On 1^{st}, 2^{nd} and 3^{rd} down the play with the highest probability of forward progress is chosen in order to get the next first down, thus increasing the EPV of the series. During each 4^{th} down, an equation is used to determine the EPV of three scenarios (1) going for the first down, or the touchdown if the goal line is closer than the distance required for a first down (2) punting (3) kicking a field goal. Whichever has the highest EPV is the choice made [7].

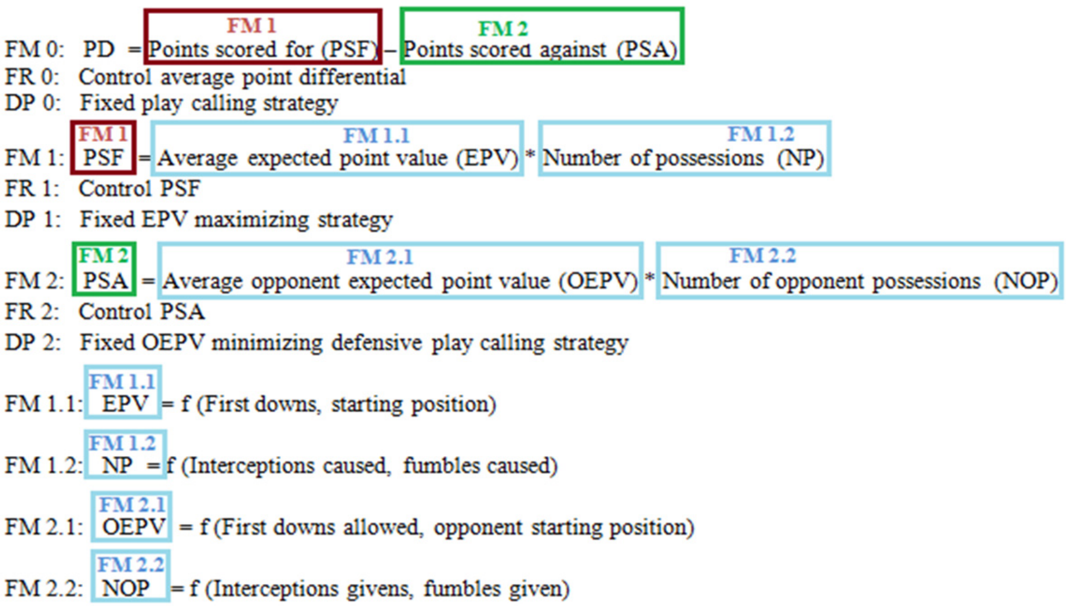

Fig. 1: Top two levels of the 5 level fixed play calling strategy design solution and FM equations for the third level

An example to illustrate making a decision using EPV would be 4th down at 5 yards to go on the opponent's 5 yard line. The user has two choices, kick a 3 point score or go for the touchdown. Based on Carter et al.'s [7] data, the probability of a making a 3 point kick can range depending on the quality of kicker and the angle, but is about 75% on average. The probably of making a touchdown for 7 points is about 25% on average. The equation for EPV considers both the chance of the getting points combined with the EPV for succeeding minus the EPV from the resulting opponent's field position if the attempt to score fails. If the field goal is missed the opponent will begin their series on their 15 yard line (-0.64 EPV). If the touchdown fails, disbarring a turnover or loss of yards, the opponent will begin their possession somewhere between their 1 and 5 yard line (-1.3 EPV).

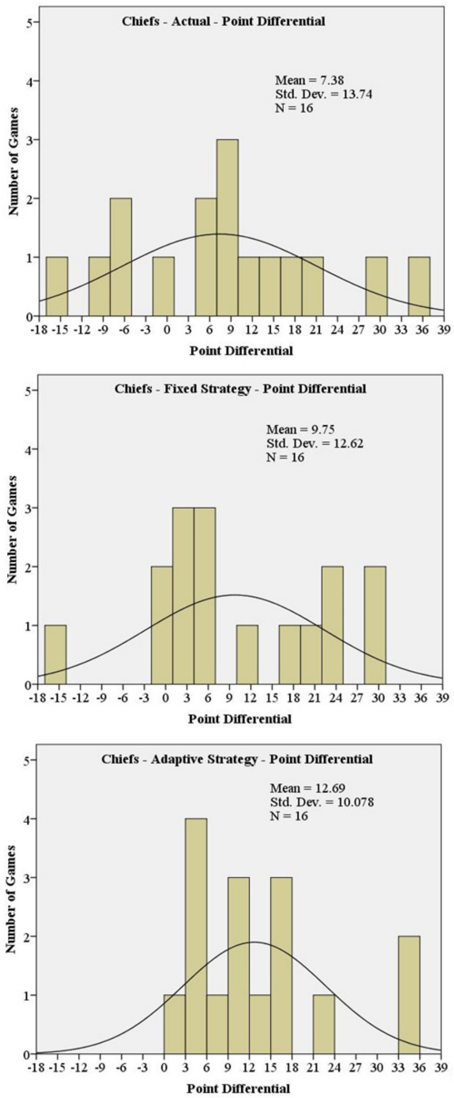

Fig. 2: Chiefs' means and standard deviations histograms

The equation for the field goal option (FGO) would be (1):

$$FGO\ EPV = \left(\left(0.75 * 3\right) - \left(-0.64\right)\right) = 2.89 \quad (1)$$

The equation for the touchdown option (TDO) would be (2):

$$TDO\ EPV = \left(\left(0.25 * 7\right) - \left(-1.3\right)\right) = 3.05 \quad (2)$$

So in this situation, using the design solutions in this work, the user would make the choice to go for the touchdown due to higher EPV.

Two changes were made to the settings for the simulations. All penalties were removed from simulations for the adaptive play calling strategy simulations. This is due to what seemed to be an uncharacteristically large number of penalties for fighting and other fouls for unsportsmanlike conduct. These are not related to the play calling, yet they can alter the result of a series, because they often grant an unearned first down. Also, the simulator features a limiter that forces injuries on a player if their yards gained on the simulated season will significantly exceed their actual totals. That limiter was switched off. This change does not prevent players from becoming injured as a part of the result of a play.

2.3. Comparing the two solutions: fixed and adaptive

The two design solutions have a few play calling differences.

With the initial, or fixed, design solution, the user chooses the offensive play that has the highest probability of success and a positive gain, factoring in what is needed to likely achieve the next first down. These gains are usually small, ranging between one and ten yards regularly, however they can consistently be relied on for a gain. The *Action! PC Football* simulator [16] displays the probability of a positive gain with each possible play choice.

There are some situations where the user calls plays with a lower probability of successful completion on 2nd or 3rd down This is due to a negative result on a previous down. To get 10 yards over 3 plays, the user needs at least 3-4 yards on average each play. Sometimes a play can result in no gain or a loss of yards, requiring the user to gain over 10 yards in 1 or 2 plays to achieve a first down. The user must then consider choosing a play that has a lower probability of a successful completion but can result in a longer gain. This is because the plays with the highest probability of successful completion are unlikely to result in the larger gain needed for a first down.

The defensive play is always the same, based on the FM of minimizing the time the opposing quarterback has to deliver the ball. This depends on the number of pass rushers and when receivers get free from defenders. Therefore a minimum of 5 players rush at the quarterback every play. In conjunction, the pass defenders play tight man on man defense to limit the quarterback's options.

At the start of the game, the adaptive design solution uses the offensive play calling strategy of the fixed design solution.

The derivative over time for each FM is monitored and changes are made if the values of the current FMs trend in an undesired direction. Similar to Cochran et al. [12] attempts to improve the standard work are made, and, if unsuccessful, a different DP can be chosen. Offensively, this DP might be the type of play being called. Similarly on defense, the number of players rushing the quarterback, the number of players in pass defense and the scheme can change as they are the DP for controlling their related FM.

Sixteen games, a full season, are played on the *Action! PC Football* simulator [16] using these strategies. The value of each FM is recorded at the end of every game and totaled for the season. The means and standard deviations for the top two levels of FMs are calculated for both design solutions and compared to those from the actual season.

3. Results

For each simulation the mean and standard deviation for points scored, opponent points and PD have been collected. The results of each design solution are compared to each other and to the actual season. Fig. 2 is an example of the compared means and standard deviations for PD. In this case, the figure shows comparisons in PD while using the Kansas City Chiefs. This specific data set was illustrated as it best represents the expected improvement when applying the design solutions. There is noticeable improvement in PD with the design solutions compared to 2015 play calling strategies, PDs of 9.75 and 12.69 for fixed and adaptive compared to 7.38 for actual. Similar results for lower level FMs can be found in Henley [17].

The means and standard deviations for PDs for the all three teams for the actual season and the fixed and adaptive design solution strategies are compared in Tables 1 and 2.

Table 1 shows the means for the FMs of the design solution's top two levels. The mean for points scored and PD for each team was higher with the design solutions' play calling than during the actual 2015 season [17].

The adaptive play calling design solution does not always do better than the fixed play calling strategy. The mean PD was lower for the Seahawks using the adaptive strategy.

The opponents points scored did not always go down with the design solutions compared to the actual season.

Table 1: Means for the regular season's 16 games

Means:	**Actual**	**Fixed**	**Adaptive**
Seahawks			
Points scored	26.44	36.13	31.00
Opponent points	-17.31	-15.50	-21.25
PD	**9.13**	**20.63**	**9.75**
Chiefs			
Points scored	25.31	31.63	33.00
Opponent points	-17.94	-21.88	-20.31
PD	**7.38**	**9.75**	**12.69**
Browns			
Points scored	17.38	25.19	26.94
Opponent points	-27.00	-29.56	-23.63
PD	**-9.63**	**-4.38**	**3.31**

The standard deviations for points scored, opponent points and PD were smaller with the design solutions' play calling than during the actual 2015 season (Table 2). There is an increase in the standard deviations for opponent points scored in the fixed solution compared to the actual season.

Table 2: Standard deviations for the regular season's 16 games

Standard deviations:	**Actual**	**Fixed**	**Adaptive**
Seahawks			
Points scored	8.39	9.12	7.63
Opponent points	11.75	8.30	7.92
PD	***14.12***	***11.59***	***9.44***
Chiefs			
Points scored	8.95	8.85	6.79
Opponent points	9.77	10.07	5.37
PD	***13.30***	***12.22***	***9.76***
Browns			
Points scored	8.71	7.67	8.66
Opponent points	7.17	10.55	6.25
PD	***12.7***	***10.89***	***10.1***

The standard deviation of the adaptive strategy could be somewhat misleading (Table 2). Excluding what could be two outliers with PDs was in the 33-36 range, positive results that exceed expectation, the standard deviation was 6.

Table 3 shows the actual, fixed and adaptive strategies win-loss records of the teams. The record for each team was better with the design solutions than the actual 2015 results. The adaptive play calling design solutions results in the best win-loss records overall.

The adaptive play calling design solution in particular offers the greatest advantage when comparing the three top level FMs included in this work. The play calling strategies designed by AD achieve better records than the actual 2015 season's play calling strategies.

Table 3: Win-loss records for the regular season's 16 games

Win-loss records:	**Actual**	**Fixed**	**Adaptive**
Seahawks	10-6	16-0	15-1
Chiefs	11-5	13-3	16-0
Browns	3-13	6-10	11-5

4. Discussion

This design process could be applicable in other sports and situations requiring winning strategies. Also, AD is more than the decomposition and metrics, which have been emphasized here. It is about compliance with the independence and information axioms. Independence is maintained (axiom one) during the decomposition in part by being CEME and the FMs help to accomplish that. In addition, minimizing information (axiom two) can be re-stated as maximizing the probability of success in fulfilling the FRs. The attention to the probability of success used here in selecting the plays, e.g., the EPV, works to comply with axiom one.

The results indicate that the design solutions in this work are superior to actual play calling in 2015. However, these results cannot be considered the same as actual games. Using a simulator, the user is able to bypass possible obstacles like player and team staff buy-in to what might be considered a radical play calling approach. The simulator also allows the use of players far beyond the point that the coaching staff would have removed them for fear of injury.

4.1. Mean PDs

The mean for points scored for each team was higher in the design solution's data than during 2015. The PD was also higher in the design solutions than during 2015**.** This might indicate that the design solutions feature a more effective offensive play calling strategy than was used in 2015. The histograms for PD in Fig. 2 for the adaptive strategy show particular improvement to 12.69 in part because there are no instances of negative PD due to an undefeated season.

There could are three reasons why the opponent's average points scored increased overall. The first is a choice to prioritize certain FMs that give the opponent higher yards gained per play but favors turnovers, compared to the actual 2015 season. The second is because as the users increase their number of scoring possessions, the opponent will have more possessions. The opponent's average points scored might increase but the users' increase more. The third reason is that at the end of the game when one team is almost guaranteed victory, different choices are often made. The defensive play scheme moves to prevent long gains and quick scores and allows the opponent to make short gains more easily. This runs out the playing time, limiting the chances for the opponent to catch the score the users.

The win-loss records are one possible result of a high positive point differential. Even though there are some undefeated seasons, the same point differential over the entire season could occur with a worse win-loss record. A higher positive point differential increases the chances of but does not guarantee wins.

4.2. Variation of the PDs

The standard deviations for points scored, opponent points and PD were smaller for the design solutions than during the 2015 season. This shows that not only are the users outperforming the opponent but the users have greater control over how much they outscore the opponent by.

One surprising result is how low the standard deviation is for the opponent's points scored. This shows that the design solutions outperform the actual 2015 play calling strategies. This is possibly more important than an improvement in the means for each stat. Improved certainty (reduced standard deviation) is an important result when designing solutions with AD because it reduces the information content (axiom two). A good design solution offers the user better control, i.e., less uncertainty.

The results for the simulated season for the Seahawks using the adaptive play calling strategy, with the one loss, might be an outlier. The two starting running backs and four of the five starting offensive linemen were injured most of the season, as was the highest scoring receiver from the fixed strategy simulation. This is not something that commonly occurs in a single season. This reduced the probability of positive gains on every play and inhibited the ability of the team to score points consistently. As a result, the opponent had the ball more often than they normally would have and therefore scored more points.

4.3. Metrics

Every simulated season had the user's team in last place in the league in every passing statistic except the completion percentage, in which each team was in the top five. Yet even so, each simulated team surpassed the PD of the team during the actual 2015 season. Many consider these passing statistics important.

This might suggest the current allocation of salary, within the league-imposed cap, by position can be improved. The increased use of running backs led to many injuries on the offensive line and to the running backs during the simulations. Teams might be better prepared to outscore their opponents with more money spent on the offensive line and running backs and less on the quarterback.

5. Conclusions

Several things can be concluded from this work: First, axiomatic design (AD) can be used advantageously to design game-winning strategies in American football. Second, AD with functional metrics (FMs) and their related parent-child equations facilitate top-down decompositions for the design of play calling strategies, which provide for scoring points and preventing the opponent from scoring points and clearly have applications in other competitive situations in games and business. Third, the key metrics resulting from the application of AD with FMs for evaluating performance details are different than many of the metrics commonly thought to be important in American football, e.g., passing yards. Fourth, play calling strategies created with AD using FMs, for both fixed and adaptive design solutions, appear to be better for winning games than the actual play calling used in the NFL.

Future work should test extending this approach, using functional metrics rigorously to other games and competitive situations. FMs and adaptive designs should be developed so that they can be applied systematically to a broad range of situations.

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Appendix A. Scoring and ball control in American football

Six points are scored when one team brings the ball across the opponent's goal line into the opponent's end zone, and then a seventh point can be scored by kicking a "point after".

The playing field between the end zones is one hundred yards long. At the beginning of each half and after each score the play starts with one team kicking off to the other. The other team can run it back until they are stopped and the ball is "downed", marking the position on the field for the start of the next play.

Offensive plays can involve combinations of running, when the ball is carried, or passing, when the ball is thrown. There are precisely defined roles and routes for each player which are play dependent. Each play continues until the ball carrier is tackled to the ground or forced out of bounds, which downs the ball.

If the offensive team has not progressed at least ten yards in four plays, or downs, then they must turn the ball over to the opponent. Therefore, on the fourth down the offensive team often decides to "punt", i.e., kick the ball down the field, thereby giving the opponent a less advantageous starting position for their series of plays. The other options are to "go for it" to see if they can manage the rest of the ten yards on the fourth play, or to try for a field goal, i.e., kicking the ball between goal posts, for three points.

If the offensive team has progressed at least ten yards in four downs, i.e. with four plays, or fewer, then they are awarded a "first down" and start again trying to get another ten yards in four downs or score.

The defensive team also has plays that often attempt to anticipate a pass or run type offensive play.

The offensive team can lose the ball as described above on downs or a punt or due to a "turnover", where a runner drops the ball in a "fumble" that is recovered by the defensive team, or where the defensive team intercepts a pass. Play then continues until the ball is downed or the defensive team scores a touchdown. The defensive can also score 2 points with a "safety" where they tackle the ball carrier in the offensive teams own end zone.

Before each play the players and coaches can consult to decide which play to run. To begin each play, the offensive and defensive players line up on either side of the ball, where it was previously downed. Once they see each other's line up they can call "audibles" to change their plays. The play starts when the "center", an offensive player who lines up on the ball, "hikes" the ball to the "quarterback".

The moment the center moves the ball the players can cross the line where the ball was placed separating the two teams. The quarterback then can hand the ball off to a running back for a running play, or pass the ball to a receiver for a passing play. The quarterback can have several receivers to pass to, depending on the defensive coverage. Defensive players can rush the quarterback, guard against a run or cover potential receivers to guard against a pass.