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Optimizing Automated Manufacturing Processes Using Axiomatic Design Methods

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Abstract

Automating industrial manufacturing processes is a task that is often easier said than done. Due to emergent behaviors in both the end item being assembled, and in the robotic assemblers themselves, it is not uncommon for a change in one aspect of the design of the combined system (product + robot assembling the product) to have unintended impacts in seemingly unrelated areas of the overall system. These emergent behaviors are usually the result of poor or incomplete mapping of all the interactions between all the characteristics of the system. However, the axiomatic method provides the tools necessary to not only begin map these interactions, but to also confirm that all the requirements of the system have been met and are organized in an optimal way.

The objective of this paper is to objectively analyze a hypothetical automated manufacturing environment, and all the aspects of its design that will be necessary for it to succeed in its mission of generating profit for the company that operates it. Currently, factories are often designed after-the-fact, after a product has been developed, and all manufacturing processes are tailored to suit it. Any defects or inefficiencies in a process are dealt with reactively, after they have already had a financial impact on the company. Instead, this paper proposes designing product and manufacturing process concurrently by utilizing the axiomatic design method, and that by doing so, it becomes possible for interactions to be fully mapped and understood before anything — product or manufacturing tools — is built. By doing things this way, this paper shows that it then becomes possible to better utilize available robotic manufacturing tools & processes.

About the Author

The author of this paper has six years of experience working for Raytheon Missiles & Defense as an electrical test engineer in one of their largest factories. They have handled both new production for both established product lines and the launch of brand new product lines. They also have experience with products that were returned from the field for maintenance and repair. They worked with both entirely manual production processes, as well as heavily automated ones. Their specific duties included conceiving and designing new production processes, improving and correcting existing processes, troubleshooting and root-cause analysis of hardware that failed testing, tracking and analyzing both first-pass yield & test failure statistics, and presenting all this information to management in the factory.

Some of the views expressed in this paper - particularly the ones in regards to the culture of a manufacturing environment - are based on the author's professional experiences in this manufacturing environment. None of the views in this paper represent the views of the Raytheon Technology Corporation, or any of its subsidiaries, and are expressly the view of the author of this paper.

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Chapter 1

Objective

Manufacturing is an inherently complicated endeavor. Previous efforts by academia to contribute to the body of knowledge regarding manufacturing is often ignored by those working in a factory, if not outright rejected. While there have been methods proposed to increase the collaboration between academia and industry, and there are benefits to be had from such collaborations [1], successful and deep collaboration between established for-profit companies and non-profit universities remains the exception, rather than the rule. Instead, factories tend to look inwards when solving their problems, and if they feel the need to seek outside of information and expertise, they reach for a trade journal before they reach for an academic one. When developing best practices in the factory, empirical observations are used almost exclusively, and any proof they may have is based entirely on statistics of past events. This means that any practices developed this way are only “best” until another corner case is discovered or a new, more efficient method is developed. Methods developed in this way are purely reactionary, and while these observation-based methods can be made to work with manual manufacturing processes, where a human is involved in every step of the process, they begin to break down as humans are removed from the manufacturing cycle. The problem is that robots and other automated manufacturing methods can only do what they are told to do, and this requires the task to be automated to be fully defined in advance (including all corner cases).

The goal of this thesis is to lay out the argument in favor of utilizing Axiomatic Design to facilitate the automation of manufacturing processes. To that end, this thesis has two prongs:
1. Manufacturing processes can be more efficiently designed with Axiomatic Design methods than they can be with existing methods that seek to improve established processes after the

fact; and 2. Robots can be better designed via Axiomatic Design methods. Taken together, this thesis makes a case that when designing automated manufacturing processes, utilizing Axiomatic Design methods will yield better results than more traditional engineering design methods.

Axiomatic Design is a rigorous design method that can quantify all aspects of a problem, and identify how they interact with one another [2]. By using the Axiomatic Design method - ideally from product conception with the customer - all aspects of a product can be objectively quantified and related to one another prior to ever drawing, designing, or building anything. In turn, in the context of the factory, this allows for all production tools - including robotics - to be identified and designed alongside the product itself.

Automated manufacturing processes are extremely complicated systems, where the factory's hardware and software must be tuned to perfectly produce the specified product in a reliable and repeatable manner. This is much easier said than done. With manual production cycles, the human laborers at each step can unconsciously work around the small variability in the parts that arrive at their bench. With a manual process, if a hole is a fraction of a millimeter off from the specified location, but still aligns with the rest of the assembly overall, the laborer installs the screw without even noticing and moves on to the next step. With the same issue on an automated process, the robot may crash as it aims for a location where there is no hole, causing both lost time and product, as well as impacting management's perception about the advantages of automated production environments. In order to successfully automate a production process, all of the aspects of the process must be accurately and precisely quantified, including all tolerances and potential failure modes.

One potential way to rigorously quantify all aspects of a production process is to use Axiomatic Design to break down all production requirements into their smallest components[3], map them to their matching physical parameters, and identify all interactions between these requirements and parameters (both intended and unintended interactions). By developing this Axiomatic Design matrix of design aspects, the whole system can be objectively evaluated for faults and risks, and all in advance of any tools being built, purchased, or deployed. Axiomatic Design has the potential to eliminate (or at least reduce) the need for continuously improving a production cycle, and can be used to minimize continuous operating costs earlier in the product's lifetime. But Axiomatic Design is not without its drawbacks.

The primary challenges with Axiomatic Design are the required up-front buy-in from management on a new design and project management philosophy (over established and accepted ones, like Six Sigma), and the significant amount of time spent up-front on designing the system on paper. Axiomatic Design cannot be shoehorned in after the fact, not without a major redesign effort, and it does not do any good if the process is not followed through to final delivery. Unfortunately, this significant up-front investment of time and effort — with nothing to show but work on paper — represents a risk to modern business thinking: if a product design effort fails, then all this time and money is viewed as wasted, with no return on investment. Every business owner wants a product to sell at the end of the day. But Axiomatic Design actually is a method used to reduce risk.

However, by taking the time to identify all problems in advance, so that they may be solved in concert with one another (instead of 'in series' as is typical with a lot of design efforts), a design team can increase their odds at arriving at a successful solution. It becomes possible to not only understand the full scope of a design effort before any CAD or calculus is done, it becomes possible to identify which problems have a lot of room to maneuver their solutions, and which have very narrow paths to success (see figure 2.2 and its relevant explanation for more information). With all of this in mind, the objective of this thesis is to prove that an automated manufacturing process can be designed using Axiomatic Design methods, that these methods can identify the challenges of automated manufacturing and how they interact with one another.

Chapter 2

Rationale

2.1 Manufacturing

The primary role of the factory is to build the products that make the company its money. Market forces determine what a product sells for, so the factory's role in maximizing profits is to minimize their own costs. This means minimizing downtime, minimizing material loss, minimizing rework, minimizing production cycle time, and maximizing the number of products that can be in-work simultaneously. More simply put: efficient management of a factory dictates that products should be built perfectly the first time, with as few interruptions and delays as possible.

Currently, factories achieve these minimization's by reacting to issues and failures as they are discovered. There are many different methods that can be used to react to production failures in a consistent way - Lean Six Sigma [4], Continuous Improvement (Kaizen) [5], Total Quality Management (TQM) [6], Plan-Do-Check-Act (PDCA) [7], and 5-Whys [8], among countless others - but all of them, by their very nature, are attempting to find their solutions after the fact. They are not capable of proactively improving or optimizing any production processes. In order to be proactive in the factory, the problem being faced must be completely quantified and defined so that an effective solution/improvement can be designed and deployed.

Alternatively, Axiomatic Design seeks to eliminate the need to improve at all, and instead 'deliver perfect' at the very start of production. To borrow terminology from manufacturing: production engineers seek to increase the "first pass yield" of their products, to build as many products successfully the first time as possible, and to do this, they are always looking to improve their processes; Axiomatic Design seeks to improve the improvement process itself. By aiming improve the "first pass yield" of the improvement processes themselves, rather than the products, Axiomatic Design is able to get closer to the root of the problems facing production. It is able to do this because the Axiomatic Design method itself is very flexible; it can be applied to anything that can be designed, not just hardware and software, but methodology as well. While Axiomatic Design often requires a larger up-front investment of non-recurring engineering time, it can be used to either optimize the manufacturing cell structure itself to decrease intra-factory lead times, or it cane be used to design the processes themselves, so that recurring time expenditures can be minimized [9] [10].

$$\begin{bmatrix} a_1 & 0 & 0 \\ 0 & b_2 & 0 \\ 0 & 0 & c_3 \end{bmatrix} \tag{2.1}$$

An uncoupled matrix

$$\begin{bmatrix} a_1 & 0 & 0 \\ b_1 & b_2 & 0 \\ c_1 & c_2 & c_3 \end{bmatrix} \tag{2.2}$$

An decoupled lower-triangular matrix

$$\begin{bmatrix} a_1 & a_2 & a_3 \\ 0 & b_2 & b_3 \\ 0 & 0 & c_3 \end{bmatrix} \tag{2.3}$$

An decoupled upper-triangular matrix

The primary way that Axiomatic Design ensures that all interactions are accounted for is the use of linear algebraic matrices. Specifically, by organizing "Functional Requirement" and "Design Parameter" (FR-DP) pairs into either a diagonal matrix (ideal) or triangular matrix (acceptable), it becomes possible to prove mathematically that a design is viable - including to what degree it is viable. Because multiplying diagonal matrices is commutative (If A is diagonal, and B is diagonal, then $C = AB = BA$), and multiplying two like-triangular matrices results in a third like-triangular matrix (multiplying two upper-triangular matrices together results in a third upper-triangular matrix of identical dimensions, *or* two multiplying lower-triangular matrices together results in a third lower-triangular matrix of identical dimensions)[11]. This means that by utilizing the Axiomatic Design method and organizing the overall design matrices for each domain in Axiomatic Design, as shown in figure 2.1, into either a diagonal matrix or triangular matrix, it becomes possible to calculate out all interactions from the definition of stakeholder requirements, all the way to process architecture, and mathematically prove that a design will work and is the optimum solution given all conditions. In Axiomatic Design, these

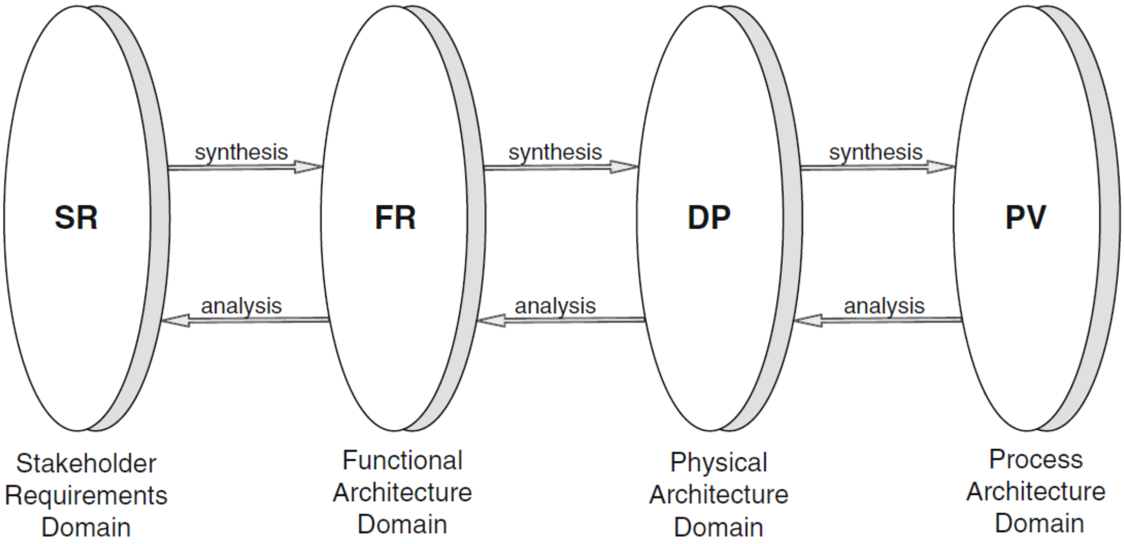

Figure 2.1: Mapping the four domains of Axiomatic Design to one another [12]

matrices are referred to as “uncoupled” (diagonal, eqn. 2.1) and “decoupled” (lower and upper triangular matrix, eqns 2.2 & 2.3). Any other matrix is considered “coupled”, and is not only undesirable in the Axiomatic Design method, but indicates that the whole design is caught in a feedback loop: any changes made to a design aspect is liable to spill over into other aspects, and eventually feedback in the originally changed aspect. A coupled matrix indicates that a design in its current state is unstable at best, and impossible at worst [2].

The challenge of Axiomatic Design is that it needs an early commitment from management, and a significant investment of time and energy from all team members in order to successfully execute it. All team members need to engage with the customers - both the internal customers and external customers - to make sure that every Design Parameter (DP) of the end product is identified, broken down into its smallest parts, quantified, and mapped to their relevant Process Variables (PVs). In order to properly do this, the DPs should also already be mapped to their respective Function Requirements (FRs), and the FRs should be mapped to their respective Customer Attributes (CAs)[1]. This will result in the four domains as shown in figure 2.1.

Part of the reason why the initial investment in Axiomatic Design is so large is that, even after all the CAs/FRs/DPs/PVs have been identified, broken down, and mapped to one another,

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[1] Earlier works by Suh utilize the term “Customer Attributes” or “CAs” [2]. In later works, Suh began using the term “Stakeholder Requirements” or “SRs”[12], in place of Customer Attributes. This can be seen in figure 2.1. In both cases, the terms “CA” and “SR” can be thought of as the requirements of the system as defined by the end-user or ’investor’.

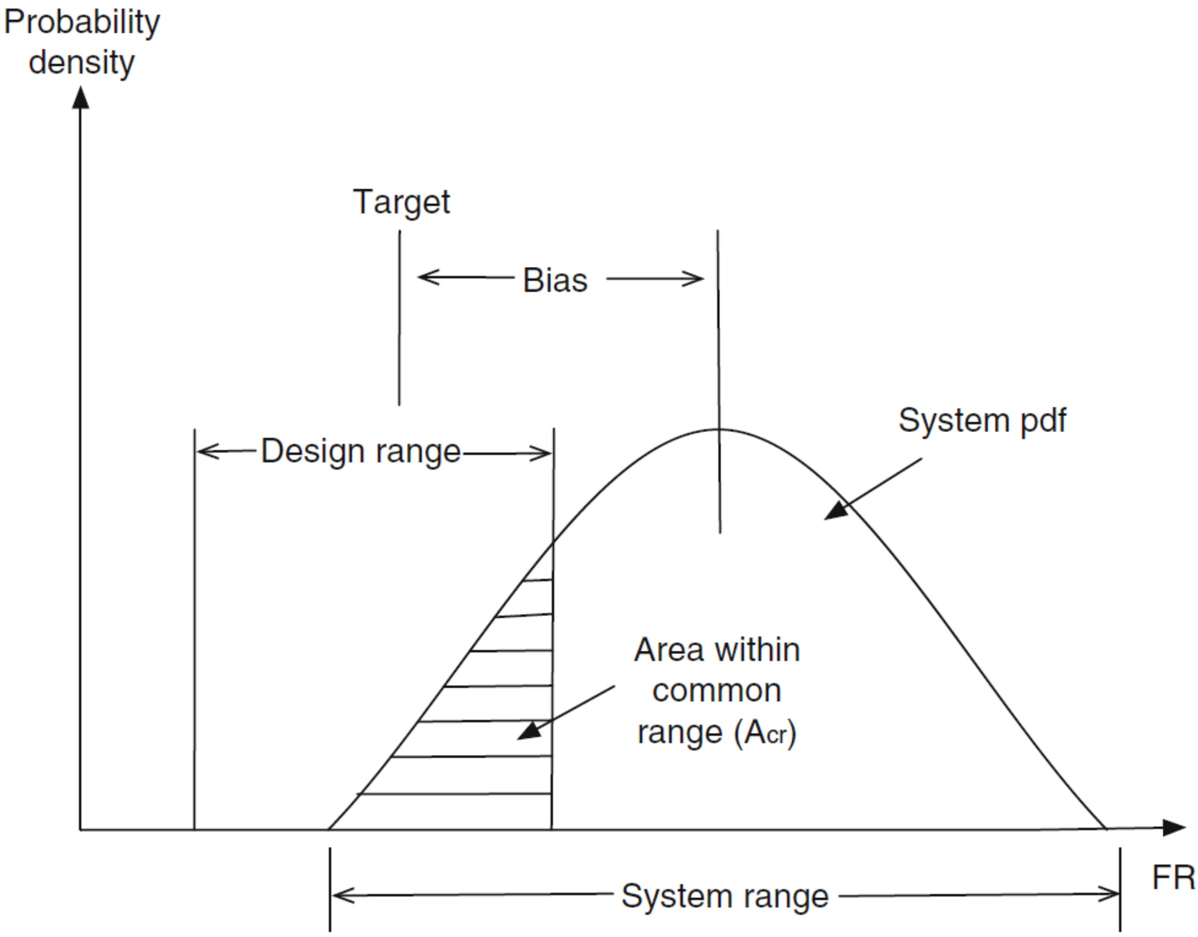

Figure 2.2: The "Area within common range" represents the overlap between the design range and the system range, illustrating the probability of a design being able to satisfy the system's requirements

[12]

they need to be quantified in such a way that the overlap between the design range (what is needed in order for the system to function) and the system range (what the system is capable of physically achieving) needs to be identified for each interaction in the Axiomatic matrices. A visual of this can be seen in figure 2.2.

But this weakness is also its greatest strength. By mapping out every interaction from customer usage to factory production, and quantifying every interaction possible, it becomes possible to actually calculate things like system performance, production yields, and customer satisfaction in advance of investing in any tools or materials. This means that whether an endeavor will be financially successful can be rigorously evaluated after the design effort has been completed, but before any building takes place. And, if it looks like a product won't be profitable enough to warrant further investment, having all of the product mapped out can facilitate a re-evaluation of customer requirements to determine if there are any CAs that can be eliminated or relaxed in order to quickly and cheaply reduce product costs, with minimal sacrifice to capabilities.

2.2 Robotics

When it comes to manufacturing, robotics can be sometimes viewed by management as more trouble than they are worth. Robots are inflexible tools. So long as the environment they exist within is consistent and within the designed expectations, they will do the same thing over and over, within a minimal amount of variability. When material or environments drift outside of design parameters, however, a robot is much less flexible than a human laborer. For example, if a robot's task is to install screws into prescribed locations in a certain order, but one particular assembly's screw hole locations are slightly out of alignment for one reason or another, then the robot will likely be unable to compensate, and at best will detect the error and 'call' a human for intervention, and at worst will crash and result in damaged product, lost time, and possible damaged tools as well. Alternatively, using a similar example of a screw, if an incorrect screw makes it into the hopper from which the robot is pulling, such as a screw with the incorrect thread pitch or damaged threads, it will similarly jam when the robot goes to install it. In both cases, a human laborer is very likely to identify the existence of the problem and document its details, all without causing damage to the product.

While robotics has potential for significant improvements to all aspects of a manufacturing cycle, if it is not carefully and deliberately designed in all of its aspects, then it can turn into an unmitigated disaster for the company. In that regard, it has been shown that robot designs can be improved by Axiomatic Design methods[13], so if these same methods are applied to the design of manufacturing robotic systems, it stands to reason that their designs can be similarly improved.

However, improving the overall design of a robotic system is only one part of the problem. The other aspect of robotics is that the system's behavior also needs to be designed as well. Traditional methods rely on designers quantifying everything in the environment themselves. While this can result in very consistent and predictable behavior, it is also very rigid and does not leave much room for the system to adapt to unexpected interruptions and variability to their routine. Instead, there is potential that Axiomatic Design methods can be used for robotic motion planning in complex environments[14], by using Axiomatic Design combined with robotics algorithms to automatically analyze an environment for goals and obstacles, and generate the best path to achieve its goals while avoiding obstacles.

So, by utilizing Axiomatic Design methods, it should be possible to: 1. Design a cellularized manufacturing facility; 2. Design the robotic hardware and tools for an individual automated production cell; 3. Design robust behavior for the robotics in any given manufacturing cell.

Chapter 3

State of the Art

At Raytheon, the current state of the art for manufacturing techniques is centered around a proprietary combination of Lean-Six Sigma [15]. It is a method that seeks to maximize part re-use, minimize assembly movement, and capture manufacturing data for use in design and process improvements. While Raytheon has found ways to utilize agile project management techniques - something typically championed by software development - for hardware projects, there remains room for further improvement. At the moment, the way a new system is brought from concept to delivery at Raytheon looks something like this:

1. Customer (govt) puts out a “Request for Proposal” (RFP), and Raytheon - among other defense contractors - respond with their proposal package. Requirements in an RFP will be broad-stroke ones; “must achieve X kph within N seconds”.
2. Assuming Raytheon’s proposal is accepted, the customer works with Raytheon to develop a more detailed list of product requirements that adhere to the requirements laid out in the original RFP. Requirements at this stage will be more technical; “Must output Y newtons of thrust, so as to achieve spec of X kph within N seconds”.
3. Raytheon further designs system to meet customer requirements, and the customer eventually accepts/rejects the design; “Must achieve a mass-flow rate of M kg/min through a nozzle throat area of A meters^2, in order to achieve the spec of Y newtons of thrust.
4. Assuming the product is accepted, the design gets rolled out to the factory, where build/test/inspection processes are developed to ensure that the product meets customer requirements.

5. Customer accepts delivery of final product(s), after reviewing the build/test/inspection data that verifies compliance with their requirements.

At the moment decisions during all of these steps are made by the relevant subject-matter experts (SMEs), and are quantified through the use of trade matrices. This process involves coming up with multiple potential design candidates, assigning weights to design priorities (the greater the importance of a design characteristic, the greater the magnitude of the weight), scoring the design candidates on their ability to satisfy individual design priorities, and then multiply the design weights against the design scores to give a total product score. An illustrative example of what a trade matrix looks like can be seen in table 3.1

		Design Candidates					
		Alpha		**Beta**		**Charlie**	
Characteristic	**Weight**	Score	Total	Score	Total	Score	Total
Strong	4	10	40	6	24	4	16
Fast	2	6	12	5	10	7	14
Cheap	5	2	10	6	30	3	15
User friendly	7	5	35	5	35	10	70
System Total			97		99		115

Table 3.1: A demonstration of the trade matrix method; design candidate Charlie wins with the greatest total score of 115

The trade matrix method is borrowed and adapted from Six Sigma. Most engineers at Raytheon stick to the 'multiple of 3' rule that helps to highlight and amplify differences in scores (not used in table 3.1), but some will use weights and scores that stick to a typical base-10 system, or even use weights that have a negative value (if there is an undesirable design characteristic that needs to be minimized or avoided). The main advantage of this method is that is allows the SMEs a lot of room to operate and do what they think is best, while still ensuring that all design options are evaluated in a consistent manner relative to one another. But there is a large drawback to this method: subjectivity. Both the characteristic weights and the design scores are assigned subjectively by the SMEs. The decisions may be informed by experience, but they are still subjective decisions, rather than objective ones. As long as a company is able to maintain an experienced workforce, they should be able to continue to succeed with this method of making design decisions. But if a company is newer, younger, or just less experienced in the area under study, it is possible that a 'wrong' weight or score may be assigned to either a characteristic or design candidate, which in turn could lead to the wrong design candidate being pursued.

Chapter 4

Methods Used

The primary method used in this design effort was Axiomatic Design, as the primary goal was to evaluate its potential in designing a production environment. The primary goals of a factory were identified based on professional experiences, and established best practices. Large leaps were avoided when decomposing Axiomatic Design pairs, instead a focus was placed on keeping individual decomposition's between layers as small as possible. These small leaps necessitated breaking each lower level down into as many as seven FR-DP pairs, but allowed for a greater control over the individual contributing factors to the overall design.

Non-technical, more human-oriented FR-DP pairs were only minimally broken down, as they were outside of the scope of the work for a design study of automated manufacturing. However, these factors cannot be ignored, and warrant continued future study; i.e. what are the human and managerial roles and best practices in an automated manufacturing environment?

4.1 The Axiomatic Design Method

As discussed in chapter 2, the Axiomatic Design method is set of rules meant to quantify the characteristics of a design challenge, including all the various interactions between the identified characteristics. When successfully applied, the designers are left with a series of linear algebra matrices that can be used to identify any impacts a design change may have. This means that not only can Axiomatic Design help to achieve successful designs, it can also be used to help maintain them in the future. A change in specifications at the CA domain can have its impact traced through the FR and DP domains, to the PR domain, all with a process not-unlike matrix multiplication.

Axiomatic Design uses two axioms — truths that cannot be derived but for which there are no counterexamples — to guide the design process[2]:

- Axiom 1: The Independence Axiom. Maintain the independence of the functional requirements (FRs) [1]
- Axiom 2: The Information Axiom. Minimize the information content of the design.

4.1.1 The Independence Axiom

In simplest terms, the Information Axiom means that when there are two or more design characteristics, the design solution must be able to satisfy each characteristic without interfering with another characteristic. Characteristics may still interact with another another (and often do) but one characteristic should not preclude the satisfaction of another. It should also be noted that this "independence" does not mean "physically independent"; a single physical part that can satisfy multiple design characteristics is considered a good design in Axiomatic Design.

Stating the idea behind the Independence Axiom in plain English: you cannot have a design with two Customer Attributes (CAs), one for a "sealed container" and the other for "accessing the items stored in the container". These two characteristics interfere with one another, and are not independent. Alternatively, the lack of independence could be introduced in the FR, DP, or PV domains, depending on what the design team comes up with for the design characteristics as they carry them through each domain. The Independence Axiom must be maintained in all four domains.

Uncoupled Designs

This is why it is desirable to have interactions only single characteristics between domains. Ideally, each CA matches to a single FR, each FR to a single DP, and each DP to a single PV. In such a case, you have three design matrices, each uncoupled as seen in equation

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[1] Note: "functional requirements (FR)" is a quote from "Axiomatic Design: Advanced and Applications"[2]. Axiom 1 is not, however, limited to the FR domain. Axiom 1 applies to all domains, and is only presented in the context of the FR domain to be consistent with the rest of the content around this quote in the book

2.1. Accomplishing this proves that all the characteristics of a design are completely independent from one another. In theory, it should be possible to freely change the design specifications and ranges for any characteristic in any domain, and not need to worry about unintended consequences in other aspects of the design. However, achieving an uncoupled design is very challenging; decoupled designs are more common outcomes. For example, an example of an uncoupled matrix between the FR and DP domains, see equation 4.1:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{4.1}$$

In equation 4.1, an X indicates an interaction between an FR and DP, and a 0 indicates no interaction between an FR and DP. In Axiomatic Design, regardless of whether a design is uncoupled, decoupled, or coupled, each characteristic in an 'earlier' domain should match with at least one characteristic in the 'next' domain: the characteristics that are actually meant to satisfy one another, FR_1 with DP_1, FR_2 with DP_2, FR_3 with DP_3, etc.

Decoupled Designs

In a decoupled design, Axiom 1 is still obeyed so long as the matrix for each domain-pair (CA-FR, FR-DP, DP,PV) forms triangular matrices of the same type (all three matrices either lower-triangle matrices, or all three matrices upper-triangular matrices). This should be achievable so long as the number of characteristics in each domain are equal with one another (such as having the same number of FRs and DPs), and they are ordered such that all interactions between domain characteristics fall on the same side of the diagonal of the matrix. For an exmaple of a decoupled matrix between the FR and DP domains, see equation 4.2

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{4.2}$$

In equation 4.2, we see a very similar design matrix as seen in equation 4.1, except there is also an interaction between FR_3 and DP_1, and FR_3 and DP_2. This extra interaction between FR_3 & DP_1 and FR_3 & DP_2 indicates that a design is decoupled, but the fact that both are located on the same side of the diagonal of the matrix also indicates that the design still obeys the Independence Axiom.

Coupled Designs

Finally, in a coupled design, you may run into coupling either when there are more characteristics in the 'previous' domain than in the 'next' domain' (Number of $FRs >$ Number of DPs), or where there are are interactions on both sides of the diagonal of the design matrix. For example, with more FRs than DPs, see equation 4.3:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \\ A_{41} & A_{42} & A_{43} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{4.3}$$

In equation 4.3, if A_{41}, A_{42}, and A_{43} are zeros, then FR_4 cannot be satisfied. If A_{41}, A_{42}, or A_{43} are not zeros, then the design is a coupled design[2].

It is also possible for a matrix to have an equal number of characteristics between domains (Number of $FRs =$ Number of DPs), and a design to be coupled as well, see equation 4.4.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & X \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{4.4}$$

In equation 4.4, there are off-diagonal interactions between FR_2 and DP_3, and between FR_3 and DP_1. This means that the Independence Axiom is still not satisfied, since any change you make to FR_2 will impact not only DP_2 but DP_3 as well, any change you make to satisfy DP_3 will have impacts to FR_2 and FR_3, and any change you make to FR_3 impacts DP_1 and DP_3. The design is caught in a loop where any time you make a change FR_2 or FR_3, those changes cascade into either DP_2 and DP_3, or DP_1 and DP_3, which in turn feed-back into their respective FRs. It may be possible to balance such a design, but it would likely only be "locally stable", to borrow the terms from controls engineering, at best. Its more likely that such a design could never arrive at a valid solution ($P_{\{m\}} > 0$, discussed further in section 4.1.2). Accounting for all of this, if the Independence Axiom is violated, the designers should go back and redesign rather than proceed with a flawed design that cannot be quantified with the Information Axiom [2][16]

Redundant Designs

It is also possible for there to be more characteristics in the 'next' domain than in the 'previous' one (Number of $DPs >$ Number of FRs), and this is called a "redundant design". When using Axiomatic Design methods, "redundancy" should not be confused with "robustness", nor should redundancy be mistaken for a desirable condition in a design. A redundant design can be either coupled, decoupled, or uncoupled, depending on how its terms are fixed. For more detail, see Case 2, section 1.7.5, of "Axiomatic Design: Advances and Applications"[2] for an example of a redundant design matrix in the FR-DP domain, and how it can be coupled, decoupled, or uncoupled depending on the choices the designers make. For the purposes of this thesis, the only thing the reader needs to know is that redundant designs can be avoided through careful application of the methods described in section 4.1.3.

4.1.2 The Information Axiom

As for the Information Axiom, its argument is that the design with the least information content is the best design. It measures this information using the units of bits, with the equation 4.5 [2]

$$I_i = \log_2 \frac{1}{P_i} = -\log_2 P_i \tag{4.5}$$

Where I_i is the total information content of the characteristic, and P_i is the probability of satisfying FR_i. When dealing with a design that has multiple characteristics (CAs, FRs, DPs, PVs), the information content for the entire system can be calculated with equation 4.6 [2].

$$I_{sys} = -\log_2 P_{\{m\}} \tag{4.6}$$

Where I_{sys} is the information content for the entire system, and $P_{\{m\}}$ is the probability that all characteristics are satisfied in a completed product. This is where the distinction between "uncoupled", "decoupled" and "coupled" becomes critical. While you can calculate $P_{\{m\}}$ for uncoupled and decoupled designs, you cannot calculate it for coupled designs since changes made to increase the probability of success for one characteristic impact the probability of success for one or more other characteristics (either negatively or positively, but indeterminately).

According to Suh, when all FRs are statistically independent, as is the case for an uncoupled design[2], $P_{\{m\}}$ can be calculated using equation 4.7

$$P_{\{m\}} = \prod_{i=1}^{m} P_i \tag{4.7}$$

This indicates that a probability of a successful uncoupled design is simply the product of success for each individual design characteristic. This means that I_{sys} can be expressed with equation 4.8[2]

$$I_{sys} = \sum_{i=1}^{m} I_i = -\sum_{i=1}^{m} \log_2 P_i \tag{4.8}$$

For decoupled designs, the math to determine the information content is similar, but slightly more complicated. $P_{\{m\}}$ involves a conditional probability for satisfying its specific design characteristic (such as FR_i), given that all other relevant characteristics ($\{FR_j\}_{j=1,...,i-1}$) are also satisfied, as seen in equation 4.9[2]

$$P_{\{m\}} = \prod_{i=1}^{m} P_{i|\{j\}} \quad \text{for } \{j\} = \{1, ..., i-1\} \tag{4.9}$$

Thus, according to Suh, I_{sys} for a decoupled design may be expressed with equation

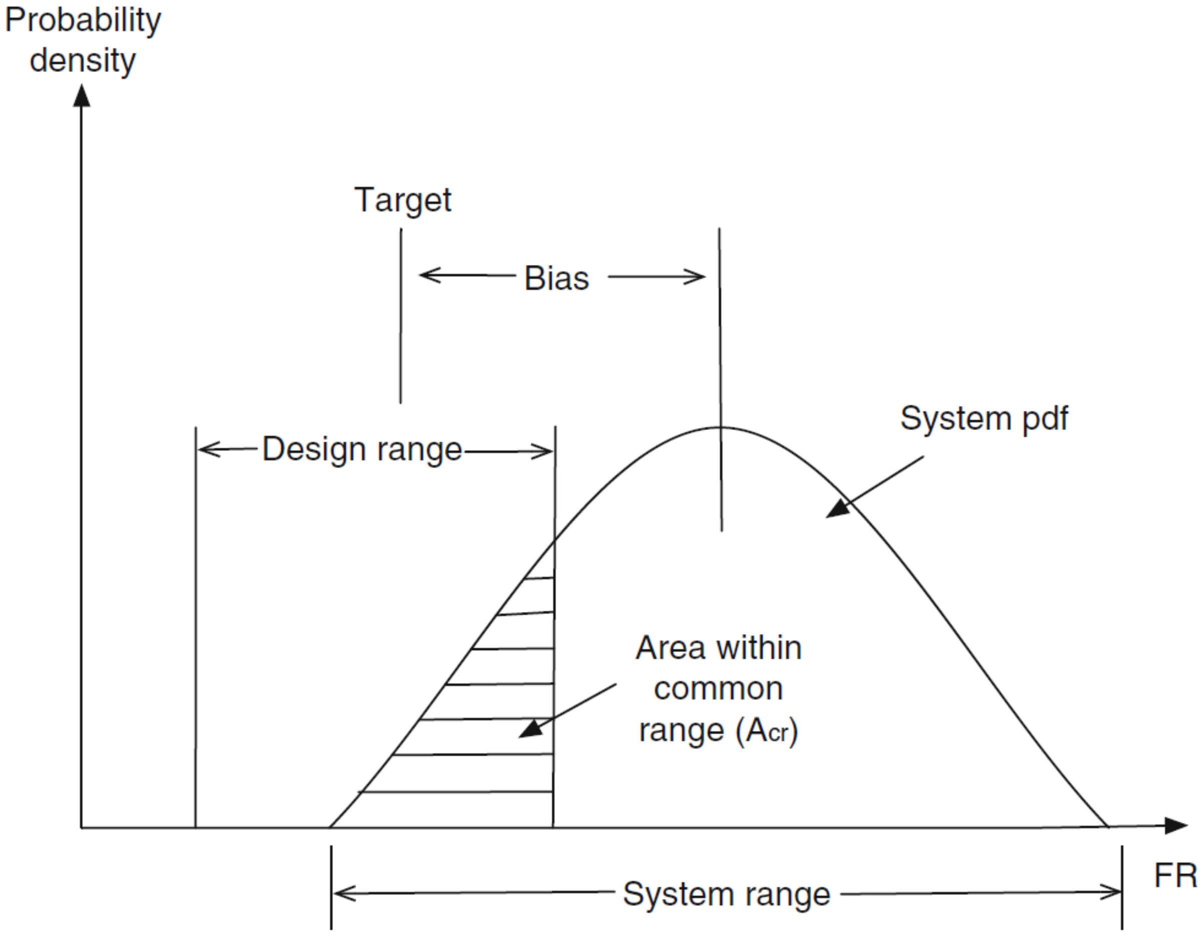

Figure 4.1: The “Area within common range” represents the overlap between the design range and the system range, illustrating the probability of a design being able to satisfy the system’s requirements

[12]

4.10[2]:

$$I_{sys} = -\sum_{i=1}^{m} \log_2 P_{i|\{j\}} \qquad \text{for } \{j\} = \{1, 2, ..., i-1\} \tag{4.10}$$

All of this — the Independence Axiom and the Information Axiom — taken together indicates that the best designs are the ones with the fewest requirements and with the easiest to ’hit’ tolerances (probability of satisfying a design characteristic). But how does one calculate the probability of successfully achieving a design characteristic? By calculating the “system PDF” that was previously shown in figure 2.2, now re-displayed as figure 4.1

In the simplest terms: the “Design Range” is what the system needs to achieve in order to function, and the “System PDF” is what the system is statistically likely to achieve when it is physically built. The overlap between these two areas — Area within common range (A_{cr}) — is the probability discussed in equations 4.7 and 4.9. A designer can maximize the overlap between these two areas by coming up with ways to increase tolerances (increasing the area of the System PDF) and/or by relaxing design requirements (increasing the design range).

It should be noted that if there is no overlap at all between the design range and the system PDF, and an overlap cannot be achieved, then the relevant $P_i = 0$ and the design has become a redundant design at the very least, and it is highly likely that the design is now coupled, as there is no longer an interaction where there should be one.

4.1.3 Axiomatic Decomposition

To build an Axiomatic Design matrix, it is necessary to “zigzag” between the domains [2]. It is necessary to move back-and-forth between the domains, “decomposing” each characteristic until all branches reach a final state that cannot be decomposed any further in either domain. Conceptually, the act of “zigzagging” can be thought of as a kind of ’closed loop control’: you have synthesis (’zig’), feedback (’zag’), inputs (’FR’), and outputs (’DP’). Figure 4.2 shows a visual of this process for the functional (FR) and physical (DP) domains. You have an FR_0 (a ’verb’ statement) that you zig over to the physical domain to come up with the matching DP_0 for (a ’noun’ statement) that would satisfy FR_0. Then you zag back to the functional domain to see if FR_0 can be decomposed into smaller parts that collectively ’add up’ to achieve the parent FR. In figure 4.2, FR_0 can be decomposed into FR_1 and FR_2. Once again, you zig back over to the physical domain to come up with the matching DP_1 and DP_2, and you zag and repeat this process until further decomposition becomes impossible. Determining when the domains can no longer be decomposed is the primary challenge for the designer.

Throughout the decomposition process, the designer must also record their intent in the form of their Axiomatic Design equation — $\{FRs\} = [A]\{DPs\}$ — at each level of decomposition[2]. This is done to verify that their decompositions are the correct ones. If a designer is able to create an uncoupled or decoupled matrix as they decompose their domains, then they know with some degree of certainty (pending review with the Information

Axiom) that their design is possible.

However, if a designer creates a coupled matrix as they decompose their matrix, they do not necessarily need to scrap their entire design. Instead, they designer may be able to rearrange their design characteristics (CAs, FRs, DPs, PVs) in such a way that the design is no longer coupled; by rearranging the design characteristics so that a triangular matrix is formed. When doing this, care must be taken to keep all rearranging consistent across all levels of decomposition and across all domains; e.g. if FR_3 needs to become FR_5 in order to eliminate coupling and create a triangular matrix, then all sub-characteristics of FR_3 need to also move to FR_5 ($FR_{3.1.2}$ becomes $FR_{5.1.2}$), and all these same changes need to be made to shift DP_3 to DP_5, CA_3 to CA_5, and PV_3 to PV_5 - and all interactions between these characteristics must also be preserved. That said, if a designer is not careful and trying to do these decompositions by-hand, it is very possible that eliminating coupling in one location may generate new couples in other layers of decomposition or in other domains.

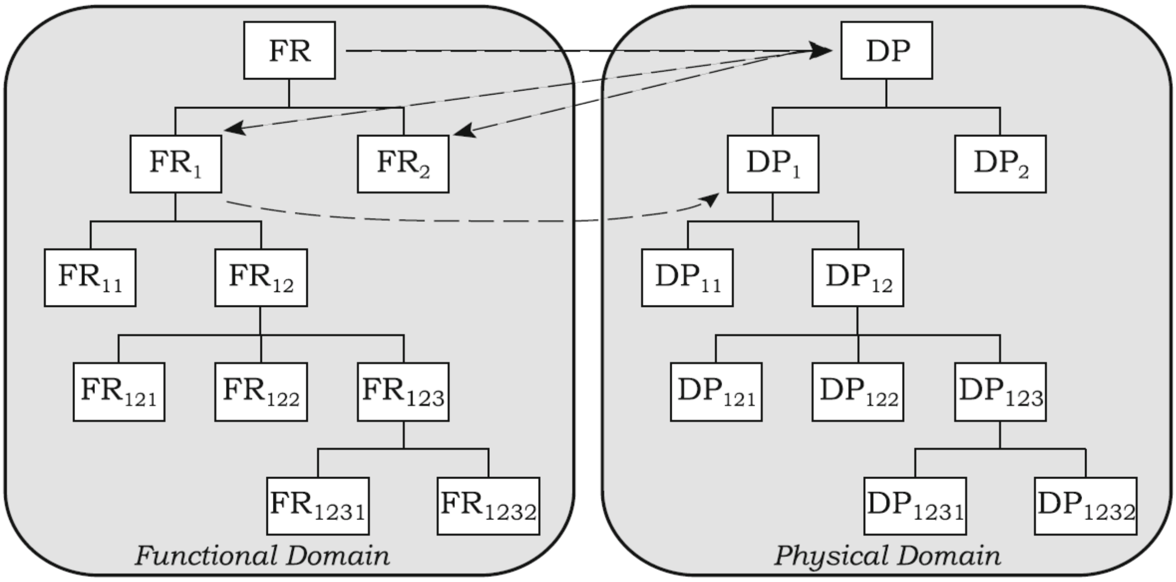

Figure 4.2: An example of the decomposing between FRs and DPs by "zigzagging" between the domains, creating the hierarchy for all the different characteristics of the two domains [12]

There are other, more advanced ways to visually represent and check a design for coupling — such as module-junction diagrams and Flow Diagrams — that can be used to visually represent relationships between different characteristics and whether a particular relationship is uncoupled, decoupled, or coupled (instead of looking at the entire matrix with multiple relationships and overall uncoupled/decoupled/coupled determination). These diagrams are difficult to generate without the aid of specialty software meant for implementing the Axiomatic Design process.

4.2 Design Matrix Studied

For this thesis, the FR-DP matrix was focused on. This was done primarily due to limitations are cropped up part-way through the research phase of this thesis. When work began on this thesis, Raytheon was initially planning on using Axiomatic Design to study potential improvements to a partially-automated production cell with four robots performing three different process steps on two different 'widgets', with human laborers also in the mix for some of the normal process steps, as well as performing re-work when an automated process failed. It was a complex environment that was experiencing poor yields and low up-time. This would have involved work in both the CA and PV domains, and allowed for a detailed and precise decomposition across all levels and domains. Unfortunately, around the same time work was about to actually begin with the automated production cell, there was a management change at Raytheon and priorities changed, and work on this thesis had to continue without access to any of the robotic systems that were initially planned for.

So, to salvage what could be from the research performed to that point, a 'general' study was done for an automated manufacturing environment, with a focus on just the FRs and DPs (since CAs are specific to what the customer wants, and PVs are specific to what is being built and what tools are available).

4.3 Tools Used

The tool used to create this Axiomatic Design matrix was Microsoft Excel. This tool was chosen out of necessity. Excel offers ways to automate and link different cells together, allowing for the creation of relatively sophisticated matrixes. However, Excel does not have have of the other design-checking and organizing tools offered by more specialized Axiomatic Design software packages.

One such specialized package would be Acclaro DFSS. Acclaro guides it user through the

Axiomatic Design process with user prompts and language checks to help avoid coupling. Acclaro can also help the user rearrange their entire matrix to eliminate coupling when it does occur, and ensure these changes are consistently carried through the entire desire (both functions that Microsoft Excel lacks; the user must do these on their own). Finally, software packages like Acclaro can automatically generate module-junction and flow diagrams as additional tools to check a design with. Unfortunately, WPI let their license for Acclaro lapse, and there was no funding to renew it. A student license for Acclaro was also more than the Author could afford and Raytheon declined to purchase a license via their various higher education funding mechanisms, either. This left the Author with a choice between Microsoft Excel, or drawing and re-drawing the matrix entirely by-hand.

Chapter 5

Results

5.1 Top Level FR-DP Pairs

The top level FR/DP pair was identified as:

FR0: Maximize the ratio between revenue & expenses in the factory	**DP0:** A system that is flexible to market conditions

Ultimately, the goal of the factory is to maximize profits, while simultaneously minimizing the costs needed to achieve those profits. The costs in a factory also must be evaluated in reference to the profits as well, as they will increase as the volume of product moving through the factory also increases. So, when minimizing costs, care must be taken that revenues are not simultaneously reduced. Or, if revenues are reduced, they are reduced by an overall smaller amount than what costs were reduced by. This is why FR0 is maximizing the ratio between revenue and expenses.

One key assumption in this thesis is that corporate strategy is not set by the factory. The factory is focused on beating their numbers from the previous quarter and year, and setting themselves up to beat their current numbers next quarter and year. Longer term planning is outside of the scope for this thesis, as this starts getting into business administration — and while Axiomatic Design can be used for coming up with a corporate strategy, that is not the goal of this thesis.

In order to satisfy FR0, it is not enough to simply reduce waste while expanding production. If a factory begins to over-produce, then demand for their products will begin to fall, leading to falling revenues. At the same time, if a factory fails to produce enough product, they may see the demand for their products skyrocket, leading to a spike in prices - but not every customer will be willing or able to purchase the products at the higher prices, and the factory starts to “leave customers on the table” that their competitors can snap up instead. So, to satisfy FR0, DP0 needs to be a system that monitors and reacts to market demands, both present and future.

Going deeper than the zeroth level, the following six pairs were identified using the Axiomatic Design method:

FR1: Match production rate with product complexity to meet current and future market demands	**DP1:** A system to evaluate market demand, both present and future
FR2: Minimize production cycle complexity	**DP2:** A system to evaluate products & processes for excessive complexities
FR3: Insure against potential supply shortages	**DP3:** An investment strategy that takes positions in the stock market that are inversed from material needs
FR4: Maintain worker safety at all times	**DP4:** A system that monitors injury occurrences, and correct root causes from the feedback
FR5: Attract the best talent available in the market	**DP5:** A program that actively engages with professionals - both young and experienced - and students, to maximize the bandwidth of the talent pipeline
FR6: Retain the best talent available in the market	**DP6:** Constant monitoring of market compensation packages, with proactive raises to match current market rates for all employees that meet or exceed performance goals

Table 5.1: First Level FR-DP Pairs

Putting all of these into an Axiomatic matrix, and checking for interactions, a decoupled matrix was found, as shown in figure 1. The only off-diagonal pair in the top-level matrix is FR2-DP1; the interaction between minimizing production cycle complexity, and a system that evaluates market demand both present and future. If it weren’t for this interaction, the top-level matrix would be uncoupled. However, even if the top-level were uncoupled, it would be possible that other pair might have off-diagonal interactions after being decomposed. Just because a higher level is uncoupled, it does not mean that lower levels cannot be decoupled or even coupled.

As FR-DP pairs 3-6 cover more company logistics and human labor, and since they do not interact with FR-DP pairs 1 and 2, they only received a basic amount of study in this paper, and are left to the readers to evaluate further. Testing for interactions should be a simple exercise: simply compare the identified FR-DP pairs at the next lower level, and check for interactions off either side of the diagonal.

Going forward, the focus of this paper will be on FR-DP pairs 1 and 2, where much of the details of automated manufacturing were found to lay.

5.2 FR1-DP1: Matching Production Rates to Market Demand

The first pair identified, over production or under production relative to product demand can easily impact the bottom line. If the manufacturing system fails to produce enough material to satisfy market demand, then sales are left uncaptured and revenues are smaller than they would be otherwise. If the factory system over produces the amount of material, relative to market demands, then prices its products may fall to level where it is either no longer profitable to sell them, or the company could even be forced to destroy their own merchandise. So, the key to achieve this functional requirement is a system that can evaluate market demand for a product, both in the present and in the future.

FR1: Match production rate with produce complexity to meet current and future market demands	**DP1:** A system to evaluate market demand, both present and future

Decomposing this, the following FRs and DPs and their interactions can be see as uncoupled in figure 2.

FR1.1: Automate as many production processes as possible	**DP1.1:** Robotic assembly processes
FR1.2: Minimize product complexity, while still achieving all customer requirements	**DP1.2:** Axiomatic product design
FR1.3: Minimize assembly process complexity	**DP1.3:** Axiomatic process design
FR1.4: Monitor current market demand for product(s)	**DP1.4:** Short-term (90 day) market survey mechanism
FR1.5: Forecast future market demand for product(s)	**DP1.5:** Long term (91-275 day) market survey mechanism

Table 5.2: FR1-DP1 Pairs

5.2.1 FR1.1-DP1.1

FR1.1 and DP1.1 is the first decomposition of the FR1:DP1 pair. They focus on automation, as the more manufacturing process are automated, the greater the control over the overall system that can be exerted.

FR1.1: Automate as many production processes as possible	**DP1.1:** Robotic assembly processes

Decomposing further, and the system begins to reach the limits of how far it can be broken down for this particular branch. The following two pairs of FRs and DPs are uncoupled in figure 3. This means that FR1.1.1 only maps to DP1.1.1 and vice versa; and FR1.1.2 only maps to DP1.1.2, and vice versa. With this, it is possible segment manufacturing processes separately from identifying which processes are repetitive (and thus can be automated). This further implies that manufacturing processes can be segmented with the intent of automating them; automated processes can be grouped around the manufacturing steps that are repetitive.

FR1.1.1: Segment manufacturing into process steps	**DP1.1.1:** Breaks in assembly where stops are possible & natural
FR1.1.2: Identify processes that can be automated	**DP1.1.2:** Repetitive motions with predictable dimensions

Table 5.3: FR1.1-DP1.1 Pairs

5.2.2 FR1.2-DP1.2

While FR1.1-DP1.1 was more focused on manufacturing processes, FR1.2-DP1.2 instead focuses on product complexity. By reducing and minimizing product complexity, not only can reliability and quality of end products be ensured, but manufacturing processes can be kept as simple as possible.

FR1.2: Minimize product complexity, while still achieve all customer requirements	**DP1.2:** Axiomatic product design

To help achieve this, Fr1.2-DP1.2 can be decomposed as such.

FR1.2.1: Maximize the number of functions each component satisfies	**DP1.2.1:** Versatile components
FR1.2.2: Minimize the number of physical components	**DP1.2.2:** Essential Components

Table 5.4: FR1.2-DP1.2 Pairs

However, due to the natures of FR1.2.2 and DP1.2.1, this matrix is only decoupled, as seen in figure 4. In this case, FR-DP1.2.1 and FR-DP1.2.2 pair together as expected, but FR1.2.2 also interacts with DP1.2.1. This is because the effort to minimize the number of physical components naturally interacts with a components versatility. Ideally, a single part satisfies every functional requirement - thus the interaction. In practice, this is not easy to achieve, and is sometimes outright impossible. Still, this interaction indicates that components should be as versatile as possible, without introducing extra functions that are not called for in the design.

5.2.3 FR1.3-DP1.3

Similarly to FR1.2-DP1.2, FR1.3-DP1.3 focuses on minimizing complexity, however it focuses on manufacturing process complexity.

FR1.3: Minimize assembly process complexity	**DP1.3:** Axiomatic process design

From the very outset of a design effort, the manufacturing processes need to be considered. It does not matter if something can be achieved mathematically on paper if it cannot be achieved with tools in 3D space. With that in mind, the less complex a manufacturing process is, not only will the factory see better yields and shorter cycle times, but it will see a shorter on-ramp to the introduction of the new product and and future changes that may be made to it. More directly stated, do not cut two holes when the task can be achieved with one.

FR1.3.1: Utilize additive manufacturing when possible & appropriate	**DP1.3.1:** Versatile processes
FR1.3.2: Utilize the minimum number of mechanical fastening steps	**DP1.3.2:** Essential process steps

Table 5.5: FR1.3-DP1.3 Pairs

Decomposing FR1.3-DP1.3, the following FR-DP pairs are shown as the uncoupled matrix shown in figure 5. In this matrix, we see that FR-DP1.3.1 only interacts with itself, FR-DP1.3.2 also only interacts with itself. This proves that a combination of additive manufacturing whenever possible and appropriate has no impact on the number of fasteners in use. However, the minimization of fasteners and the utilization of additive processes (when viable) are both still desirable aspects per their parents FR1.3: minimize assembly process complexity.

This may seem counter-intuitive at first, however it becomes clearer when you consider that 3D printing not only can reduce the number of parts (via the designer combining them together), but it can also *increase* the number of parts, too, if the desired part cannot be fit into the available printer volume as a whole piece. How a product is put together is a task that is up to the designer. While 3D printing can enable novel ways of assembly (or completely eliminate the need for assembly at all, via print-in-place designs), it is not necessarily a guarantee of fewer assembly steps or fasteners, either. It is just another tool in the engineer's belt.

5.2.4 FR1.4-DP1.4

FR1.4 & DP1.4 are focused on immediate demand for the products of a company. They should be evaluated in the context of material movement within the company itself. Neither FR1.4 nor DP1.4 has any interactions with any other functional requirement or design parameter at the 1.x level. Additionally, looking at the highest matrix, we can see that while FR2 and DP1 do, in fact interact with one another, as will be covered further on in this paper, DP1.4 does not interact with any of the decomposed FRs of FR2. Thus, it can concluded that neither FR1.4 nor DP1.4 will have any further interaction with any FRs or DPs outside of its own. FR1.4-DP1.4 is functionally independent from the rest of the Axiomatic matrix, indicating that material inside of the factory that this thesis is meant to represent can be moved freely to meet immediate market demand, without impacting the automated processes used to satisfy that demand. While scaling up beyond maximum capacity will still naturally require investment in additional tooling and personnel, this realization indicates that such a factory could be scaled *down* to match demand.

FR1.4: Monitor current market demand for product(s)	**DP1.4:** Short-term (90 day) market survey mechanism

5.2.5 FR1.5-DP1.5

Similar to FR1.4-DP1.4, FR1.5-DP1.5 is also focused on market demand. Unlike FR1.4-DP1.4, FR1.5-DP1.5 is focused on long term demand is intended to be used to look at a factory's *external* material position; supplier availability, material lead times, etc. Material needs to arrive at the factory with enough time left to still be turned into products that can meet time-dependent and cyclical demand.

Also like FR1.4-DP1.4, FR1.5-DP1.5 does not interact with any other FR or DP at its own level, and is functionally independent because of it.

FR1.5: Forecast future market demand for product(s)	**DP1.5:** Long term (91-275 day) market survey mechanism

Because both FR1.4-DP1.4 and FR1.5-DP1.5 are both functionally independent - including from each other - and have little to do with automation, a more further decomposition and a detailed analysis is being left as a future area of study.

5.3 FR2-DP2: Evaluating Production Cycle Complexity

While FR1-DP1 was primarily focused on material and tool management, FR2-DP2 is directly focused on production management. Specifically, it requires a minimization of complexity in a production cycle. A simple production cycle minimizes movement, reduces manufacturing steps, and keeps waiting times during and between steps as short as possible. Part of the way this can be achieved is by saving repetitive tasks for automated tools (robots), as human error is one of the key drivers of rework and process variances. To this point, if the goal is minimize the number of human laborers performing repetitive processes, and every product is assembled from a minimum (finite) amount of processes, then it would be logical to simultaneously maximize the number of repetitive processes needed to manufacture an item and ensure that enough automated systems existed to handle these repetitive processes. More directly put: automate as many process steps as coast-effective, and save the human labor for where it is really needed.

To this point, looking again at figure 1, we can see an interaction between FR2 and DP1, as it is this particular pairing where - after decomposing both - we see that production cycles begin to interact with market demand.

FR2: Minimize production cycle complexity	**DP2:** A system to evaluate products & processes for excessive complexities

Decomposing FR2-DP2, we get the following pairs, which produce the decoupled matrix shown in figure 6. The only off-diagonal pair that makes this decoupled is FR2.3-DP2.2, which indicated that a minimization of information content in overall product assembly processes also has a necessary interaction with the Axiomatic Design of the product itself. What this tells us, in more plain terms, is that manufacturing processes must be considered and designed in parallel with the product design itself. A product cannot be delivered to a factory, for manufacturing processes to be figured out after the fact, and still be considered a product designed with Axiomatic Design process.

FR2.1: Minimize the number of repetitive assembly processes performed by laborers	**DP2.1:** Automated simple & repetitive assembly steps
FR2.2: Minimize information content of product designs	**DP2.2:** Axiomatic Design of design parameters (DPs)
FR2.3: Minimize information content of overall product assembly process	**DP2.3:** Axiomatic Design of process variables (PVs)

Table 5.6: FR2-DP2 Pairs

5.3.1 FR2.1-DP2.1

Decomposing FR2.1-DP2.1, and we get the following pairs, expressed as a decoupled matrix in figure 7. The only off-diagonal pair that makes this decoupled is FR2.1.2 and DP2.1.1, which indicates that a minimization of individual process step complexity has a direct interaction with any continuous improvement process to make a product and manufacturing process be automation-centric. When looking to replace manual labor with an automated process, the complexity of the process must be both considered and minimized when possible, if it is to succeed in a automated environment.

FR2.1.1: Replace a manual laborer with an automated tool wherever cost-effective	**DP2.1.1:** A continuing improvement process to improve product & process to be automation-centric
FR2.1.2: Minimize individual process step complexity	**DP2.1.2:** Minimum number of actions to complete step
FR2.1.3: Utilize all available automated assembly tools	**DP2.1.3:** Minimum automated tool downtime

Table 5.7: FR2.1-DP2.1 Pairs

These pairs are primarily focused on keeping an assembly process as automated and automation-friendly as possible.

5.3.2 FR2.2-DP2.2

Decomposing FR2.2-DP2.2, and we get the following pairs, expressed as a decoupled matrix in figure 8.

FR2.2.1: Include only one FR per customer attribute	**DP2.2.1:** A list of all customer attributes
FR2.2.2: Exclude any FRs that do not map directly to a customer attribute	**DP2.2.2:** Essential features

Table 5.8: FR2.2-DP2.2 Pairs

These pairs are focused on minimizing the information content of the product design by ensure that all the customer requirements are accounted for, with no cases of extra features being included 'just because'. The only off-diagonal interaction making this particular sub-matrix decoupled is FR2.2.2-DP2.2.1, which is the interaction between excluding FRs that do not map to a customer attribute, and the list of customer attributes itself. This basically states that the engineer cannot be tempted to help by introducing FRs that the customer did not ask for. To do so could potentially destabilize the design in unpredictable ways. Design scope creep should be avoided under all circumstances, unless directly requested by the stakeholder.

5.3.3 FR2.3-DP2.2

In figure 6, it is shown that there is an off-diagonal interaction between FR2.3 and DP2.2, and this is what makes FR2-DP2 decoupled instead of uncoupled. For convenience, FR2.3's and DP2.2's respective decompositions are listed here again. Figure 10, shows another decoupled matrix, with all interactions being off of the primary diagonal of the overall Axiomatic matrix. For FR2.3.1, it interacts with both DP2.2.1 and DP2.2.2, because all necessary quality standards should interact with all customer attributes and all essential features of a product. For FR2.3.2, minimizing the number of assembly steps in a manufacturing process will only interact with the essential features of a product - as the elimination of extra features will naturally eliminate extra assembly steps.

FR2.3.1: Specify only the quality standards necessary for the end product	**DP2.2.1:** An exhaustive list of all customer attributes
FR2.3.2: Minimize the number of assembly steps in a process	**DP2.2.2:** Features only as-specified, with no 'just because' extras.

Table 5.9: FR2.3-DP2.2 Pairs

5.3.4 FR2.3-DP2.3

Like FR2.2-DP2.2, FR2.3-DP2.3 is also focused on minimizing information content, but in this case, it is focused on minimizing the information content of manufacturing processes. Decomposing FR2.3-DP2.3, we get the following pairs, expressed as an uncoupled matrix in figure 9.

FR2.3.1: Specify only the quality standards necessary for the end product	**DP2.3.1:** Fully mapped design requirements
FR2.3.2: Minimize the number of assembly steps in a process	**DP2.3.2:** Products broken into manageable sub-assemblies

Table 5.10: FR2.3-DP2.3 Pairs

5.4 FR2-DP1: Production Cycle Complexity in terms of Market demand

With FR2-DP1, we start seeing interactions that are exclusively off-diagonal, in reference to the overall Axiomatic matrix for this design. The FR2-DP1 pairing is the primary driver keeping this design from being uncoupled, but it is not the only driver of it.

FR2-DP1 represents the interaction between production cycle complexity and material movement within the production environment. Their decompositions are listed in 5.11, and the resulting matrix with all of their interactions shown in figure 11. All of these interactions are about the way the minimization of information content in all aspects has interactions with the design and assembly processes, but no interactions with the supply chain itself.

FR2: Minimize production cycle complexity	**DP1:** A system to evaluate market demand, both present and future

As stated early, FR2 does not interact with DP1.4 or DP1.5 in any way. However, all decompositions of FR2 do interact with DPs 1.1, 1.2, and 1.3. FR2.1 interacts with DPs 1.1, 1.2, and 1.3, as minimizing repetitive labor performed by humans has interactions with robots performing repetitive tasks, as well as Axiomatic Design of both products and processes. FR2.2 only interacts with DP1.2, as both deal with product design, and FR2.3

only interacts with DP1.3, as both deal with process design.

FR2.1: Minimize the number of repetitive assembly processes performed by laborers	**DP1.1:** Robotics performing repetitive assembly processes
FR2.2: Minimize information content of product designs	**DP1.2:** Axiomatic product design
FR2.3: Minimize information content of overall product assembly process	**DP1.3:** Axiomatic process design
	DP1.4: Short-term (90 day) market survey mechanism
	DP1.5: Long term (91-275 day) market survey mechanism

Table 5.11: FR2-DP1 Pairs

5.4.1 FR2.1-DP1.1

Diving deeper and looking at the decomposition of FR2.1-DP1.1, we get the following FRs and DPs, which combine to create the decoupled matrix seen in figure 12. In the process minimizing the number of repetitive assembly processes performed by manual laborers (FR2.1), we see the the only interactions with Robotic Assembly processes (DP1.1) are when replacing the manual laborer (FR2.1.1) interacts with breaks in the assembly process (DP1.1.1) and repetitive motions (DP1.1.2). For minimizing the process step complexity (FR2.1.2), we only see an interaction with the repetive motions themselves (DP1.1.2).

FR2.1.1: Replace a manual laborer with an automated tool wherever possible	**DP1.1.1:** Breaks in assembly where stops are possible & natural
FR2.1.2: Minimize individual process step complexity	**DP1.1.2:**Repetitive motions with predictable dimensions
FR2.1.3: Utilize all available automated assembly tools	

Table 5.12: FR2.1-DP1.1 Pairs

5.4.2 FR2.1-DP1.2

Looking at the decomposition of FR2.1-DP1.2, we get the following FRs and DPs, which combine to create the decoupled matrix seen in figure 13. In this case, there is only one interaction at this level: between FR2.1.2 and DP1.2.2. In the effort to minimize process step complexity, it will become necessary to consider which components are truly necessary and how they are necessary.

FR2.1.1: Replace a manual laborer with an automated tool wherever possible	**DP1.2.1:** Versatile components
FR2.1.2: Minimize individual process step complexity	**DP1.2.2:** No 'extra' parts
FR2.1.3: Utilize all available automated assembly tools	

Table 5.13: FR2.1-DP1.2 Pairs

5.4.3 FR2.1-DP1.3

Looking at the decomposition of FR2.1-DP1.3, we get the following FRs and DPs, which combine to create the decoupled matrix seen in figure 14. For this decomposition, we have two interactions: FR2.1.1 & DP1.3.1; and FR2.1.2 & DP1.3.2. For the first pair (FR2.1.1-DP1.3.1), when replacing a manual process with an automated one, the automated one should be as versatile as possible. This is means that the automated process should be able to identify, and compensate for any reasonable part variabilities, and it should also be able to deal with a part that is out of spec on its own (ejecting a non-conforming part from the assembly line into a waste/scrap bin, obtaining a replacement, and continuing on without human interaction). For the second pair (FR2.1.2-DP1.3.2), this goes to keeping the overall assembly process as simple as possible. All individual steps should be as simple as possible, and it should use as few steps as necessary to complete the goal. More directly stated: the “keep it simple, stupid” (KISS) principle, and minimize product movement.

FR2.1.1: Replace a manual laborer with an automated tool wherever possible	**DP1.3.1:** Versatile processes
FR2.1.2: Minimize individual process step complexity	**DP1.3.2:** No 'extra' process steps
FR2.1.3: Utilize all available automated assembly tools	

Table 5.14: FR2.1-DP1.3 Pairs

5.4.4 FR2.2-DP1.2

Looking at the decomposition of FR2.2-DP1.2, we get the following FRs and DPs, which combine to create the decoupled matrix seen in figure 15. For this off-diagonal matrix, both FR2.2.1 and FR2.2.2 interact with just DP1.2.2. Both FR2.2.1 and FR2.2.2 deal with limiting scope creep, so both must interact with keeping a design limited to just its essential components. If a designer succeeds in only having one FR per customer attribute (which they should, if they are properly following the setup for Axiomatic Design), and excludes all FR that do not map directly to a customer attribute (at all levels), then all that should remain are the components essential to a design.

FR2.2.1: Include only one FR per customer attribute	**DP1.2.1:** Versatile components
FR2.2.2: Exclude any FRs that do not map directly to a customer attribute	**DP1.2.2:** No 'extra' parts

Table 5.15: FR2.2-DP1.1 Pairs

5.4.5 FR2.3-DP1.3

Looking at the decomposition of FR2.3-DP1.3, we get the following FRs and DPs, which combine to create the decoupled matrix seen in figure 16. Conversely, compared to FR2.2-DP1.2, FR2.3-DP1.3 is a situation where only FR2.3.2 interacts with the decomposition of DP1.3. In this case, it interacts with both DP1.3.1 and DP1.3.2. By minimizing the number of assembly steps in a manufacturing process, interactions with both the creation of versatile processes and utilizing essential process steps are seen. However, no interactions are seen between the quality standards, and how versatile or essential a process step is. This suggests that quality does not need to be sacrificed in order to successfully design a manufacturing process with Axiomatic Design methods.

FR2.3.1: Specify only the quality standards necessary for the end product	**DP1.3.1:** Versatile processes
FR2.3.2: Minimize the number of assembly steps in a process	**DP1.3.2:** No 'extra' process steps

Table 5.16: FR2.3-DP1.3 Pairs

5.5 FR3-DP3: Material Procurement Strategies

FR3-DP3 is uncoupled, at least to the levels that is was decomposed to. However, FR3-DP3 also deals with parts of the automated production cycle that cannot be completely ignored, but do not have much to do with automation itself; these fall outside of the scope of work, and were only included to complete the decomposition of FR0-DP0. It is possible that FR3-DP3 could also change from uncoupled to decoupled as it is decomposed. However, as long as each layer is decomposed correctly, it is unlikely that they will become coupled in this case.

Specific to FR3-DP3, the primary role of this pair is to financially insulate the company against supply chain shocks. A company can only control where they purchase their materials; they cannot control the market value of those materials. If raw material prices skyrocket, a company may not be able to afford to actually purchase the materials at a price that would allow production to remain profitable. However, if raw material values were to crater, a company may find themselves in financial trouble if any stores of those materials were used to secure loans. So, as a way to help insure against such shocks, a strategy of commodity options contracts can be used as a way to offset risk. If material prices skyrocket, some call options contracts can allow for the purchase of materials at a lower price point. If material costs significantly decrease, put options contracts can be used to sell material at the older, higher price (potentially helping to cover the balance on a loan that was previously secured via the same material).

FR3: Insure against potential supply shortages	**DP3:** An investment strategy that takes positions in the stock market that are inversed from material needs

The decomposition of FR3-DP3 can be seen in figure 17.

FR3.1: Hedge against raw materials in storage losing their value	**DP3.1:** Utilize Put Options contracts to take a 'short' position against all raw materials that must be kept on-hand
FR3.2: Hedge against price increases in raw materials needed to satisfy orders	**DP3.2:** Utilize Call Options contracts to take a 'long' position against all raw materials that must be purchased in the future to satisfy existing and forecasted orders
FR3.3: Hedge against outsourced component shortages	**DP3.3:** Utilize multiple sources of qualified component suppliers

Table 5.17: FR3-DP3 Pairs

5.6 FR4-DP4: Personnel Safety

FR4-DP4 deals with laborer safety. With very few exceptions, every factory needs human laborers. While there are some factories that can go “lights out” (no humans; fully autonomous machines building product in the dark), these are few and far between, and they require the product to be designed from the ground-up for 100% automated assembly. For every other factory, the introduction of robots represents a mixture of another risk to worker safety that needs to accounted for and minimized, as well as reduction of overall risk. While an individual robot represents a risk to the laborers around it - the same as a CNC machine would, it also represents an elimination of risk by removing a human from the labor equation as well. The only to 100% eliminate risk to a laborer is to remove that laborer from the work environment all together. Robotics is one of the few technologies that can accomplish this. Meanwhile, when introducing a robot, care must be taken to install the appropriate barriers and interlocking systems to ensure that a laborer cannot be accidentally injured.

FR4: Maintain worker safety at all times	**DP4:** A system that monitors injury occurrences, and correct root causes from the feedback

Like FR3-DP3, worker safety (specific to how to keep them safe) is largely outside of the scope of this thesis. Care must be taken to design safe robotic manufacturing cells, but they do not play a role in employee attraction or retention when they are made safe to work around. It is likely that failing to design a safe robotic system will result in a negative impact to employee retention, however this was not revealed in the decomposition in 1. This suggests that there is further decomposition to be made for both FR-DP4 and FR-DP6, or that the interaction may be revealed in an analysis of the CA-FR or DP-PV matrices.

Unlike FR3-DP3, FR4-DP4 is not an uncoupled matrix. There are interactions between FR4.4-DP4.3, and FR4.6-DP4.2. The decomposition of FR4-DP4 can be found in table 5.18, and its matrix can be seen in figure 18

FR4.1: Capture all instances of recordable injuries	**DP4.1:** A consequence-free, injury reporting tool (reactive safety)
FR4.2: Determine root cause of recordable injuries	**DP4.2:** An independent accident & safety investigation team
FR4.3: Track injury rates relative to production areas	**DP4.3:** A tool for consistently logging data about accidents
FR4.4: Track injury rates relative to production tasks	**DP4.4:** A tool for feeding back safety data to process designers
FR4.5: Make feedback about injury data available to all employees	**DP4.5:** A system for disseminating statistics about safety & accident trends, and safe work practices
FR4.6: Create a system for anonymously and privately reporting safety concerns	**DP4.6:** A consequence-free safety-concern reporting tool (proactive safety)

Table 5.18: FR4-DP4 Pairs

5.7 FR5-DP5: Talent Attraction

Since this hypothetical factory cannot operate without human labor still, recruiting talent still needs to be considered for the factory. Even if all the manual tasks could be completely automated, there would still be a need for other support roles elsewhere in the company.

FR5: Attract the best talent available in the market	**DP5:** A program that actively engages with professionals - both young and experienced - and students, to maximize the bandwidth of the talent pipeline

The decomposition of FR5-DP5 can be found in table 5.19, and its matrix can be see in figure 19.

FR5.1: Offer average to above-average starting pay	**DP5.1:** A system to monitor average pay, relative to responsibilities, at direct competitors
FR5.2: Recruit top-performing employees from direct competitors	**DP5.2:** A program for collecting, publishing, and presenting the most technically interesting work currently being performed at the company by top-employees
FR5.3: Recruit from ABET accredited engineering schools	**DP5.3:** Co-op partnerships with programs teaching skills relevant to the business

Table 5.19: FR5-DP5 Pairs

5.8 FR6-DP6: Talent Retention

With the attraction of talent comes the retention of talent. While the two may seem related at first glance, the reasons that people join a new company actually tend to be quite different from the reasons someone might leave their current company. Management can't control why someone would want to leave their old role, so all that can be done is offer more money than other companies competing for the same talent, so that new talent may be more easily attracted. But management can make efforts to retain the talent they already have. Money is a large part of this as well, but in the case of retention, it also involves increasing the amount of money an employee receives each year - through direct pay, bonuses, and benefits - so that they do not feel any financial need to begin looking at what roles at other companies are listing for their salaries.

It should be noted that without further decomposition "raises" is a stand-in for the complicated topic of the relationship between labor and capital, a discussion that becomes even more complicated (and important) in automated manufacturing environments.

FR6: Retain the best talent available in the market	**DP6:** Constant monitoring of market compensation packages, with proactive raises to match current market rates for all employees that meet or exceed performance goals

The decomposition of FR6-DP6 can be found in table 5.20, and its matrix can be seen in figure 20.

FR6.1: Increase pay rate improvements to meet or beat competitor's	**DP6.1:** A system to monitor increases in compensation across the market
FR6.2: Sharing profits with employees	**DP6.2:** Bonuses paid out relative to profit goals
FR6.3: Make employees stakeholders in company ownership	**DP6.3:** Offer long stock option contracts to employees
FR6.4: Offer generous retirement plans	**DP6.4:** Offer employees employees generous plan contributions, and investment flexibility
FR6.5: Offer generous health plans	**DP6.5:** Keep employee out-of-pocket costs for medical expenses to a minimum
FR6.6: Hold managers accountable to their direct reports	**DP6.6:** A system for employees to review the performance of their direct managers, as a factor in the manager's performance regular performance reviews
FR6.7: Maintain a healthy work-life balance	**DP6.7:** Offer ample time off for life outside of work (child leave, PTO, sick time, flexible working schedules, etc), and not only make is possible to utilize this time, but encourage them to

Table 5.20: FR6-DP6 Pairs

For FR-DP pairs 3, 4, 5, and 6, all of them are included through their first decompositions to ensure that FR0-DP0 is truly decoupled. However, none of them appear to directly interact with FR-DP pairs 1 or 2, where the primary focus of their thesis was: robotics and automation in a manufacturing environment. FR-DP pairs 3, 4, 5, and 6 all merit further study and likely can be decomposed into more layers.

Chapter 6

Conclusion

By utilizing Axiomatic Design, not only can an entire automated factory be designed, but its supply chain can be made independent of its process cycle. It also becomes possible to determine which aspects of a product design are important to emphasize to help ensure the greatest financial success in the factory. Finally, using Axiomatic Design, becomes straightforward to identify and understand all the ways certain changes to both a product or a process could impact the overall yield and cycle time in the factory.

Interestingly, it seems that there are no interactions between the automated portions of the factory and the human portions, at least in terms of worker safety, attracting talent, and retaining talent. This was a surprising observation, and runs counter to the author's own experiences working in one of Raytheon's factories. There initially was an expectation to find interaction between automated production cycles and the number of workers required on the fringes needed to support them - not unlike robots sitting inside of an imaginary volume and human laborers residing on the surface of that same volume, with both being necessary to successfully complete a production cycle.

A potential explanation for the lack of interactions between automation and worker safety, attraction, and retention is that by introducing robotics, you naturally eliminate the need for all three of these items for that particular position. If a task is automated, you do not need to attract nor retain talent for it. If a task is automated, there is no human present to be injured. Thus, it makes sense that there would not be any interactions between these three 'human' aspects of the Axiomatic Design matrix, and automation.

A possible limitation of this work was also identified upon peer-review: it is possible that this design only works when a company already has a dominant position in its market. No consideration was made for growth of the company in the Axiomatic Design matrix, only growth of markets and a company's share of it. This is likely the result of author bias. It may be possible to eliminate this bias with additional work; through further decomposition, working with the other domains, or changing the overall design itself.

This matrix still requires further study. Additional decompositions of FR4, FR5, FR6, and their matching DPs will likely reveal further information about automating a factory. It is possible that there are additional considerations in regards to all three of these FRs when it comes to laborers that are working in the periphery of an automated production cell, but all should be studied with the input of social scientists, as well as industry experts. FR3 also merits further decomposition to reveal more detail about the finances of running an automated factory, and those with experiences in business administration should be engaged here. FR1 and FR2 can also be further decomposed, but doing so will likely require a specific manufacturing challenge to guide the decomposition process; an end goal (product) will need to be considered, so that its manufacturing process has a fixed set of CAs that FRs, DPs, and PRs can be designed for. Introduction of CAs and PRs could reveal interactions that are not visible in the FR-DP matrix.

In conclusion, while there is still more work to be done, this thesis proves that it is possible to design at least a decoupled automated manufacturing process.

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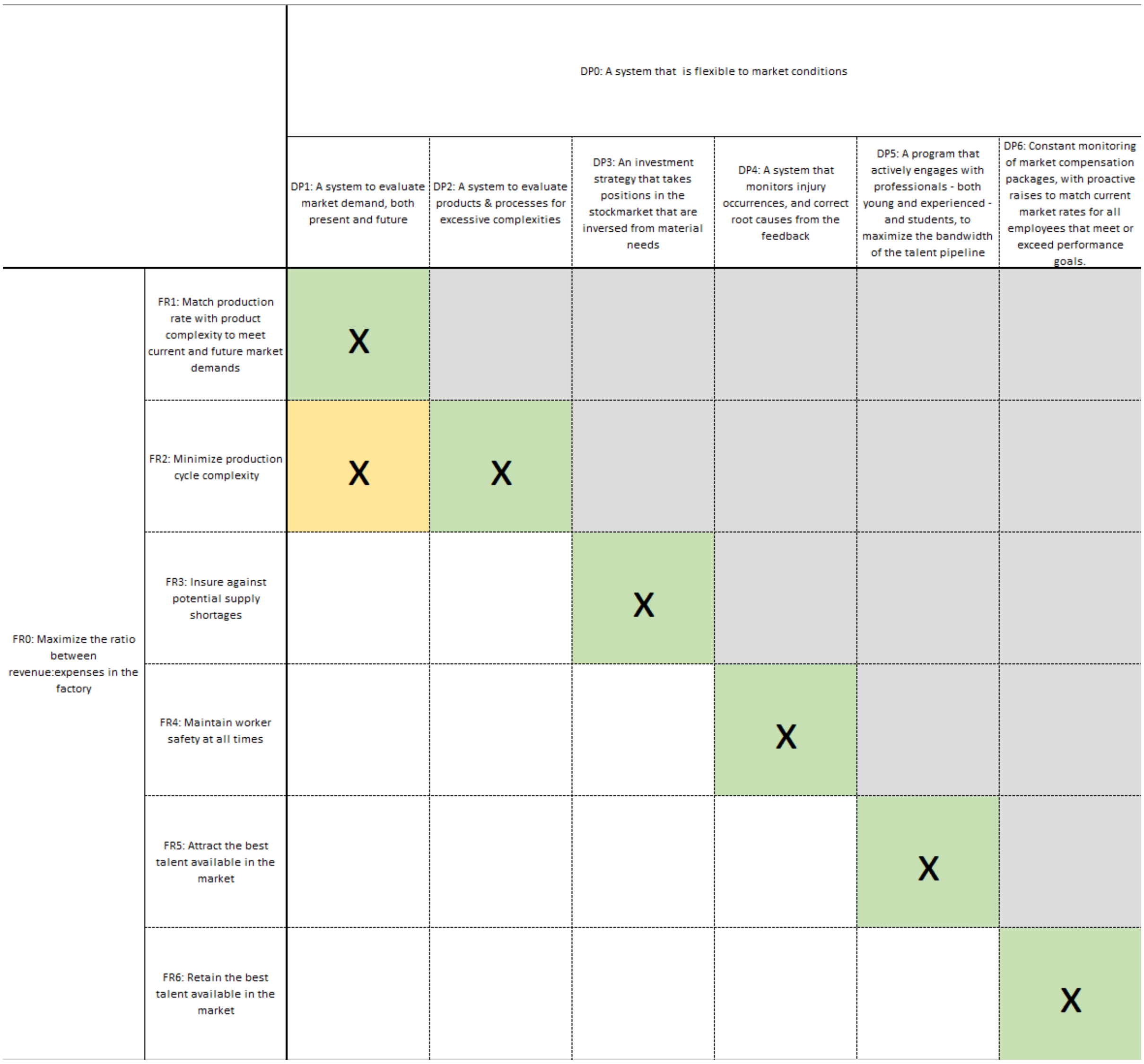
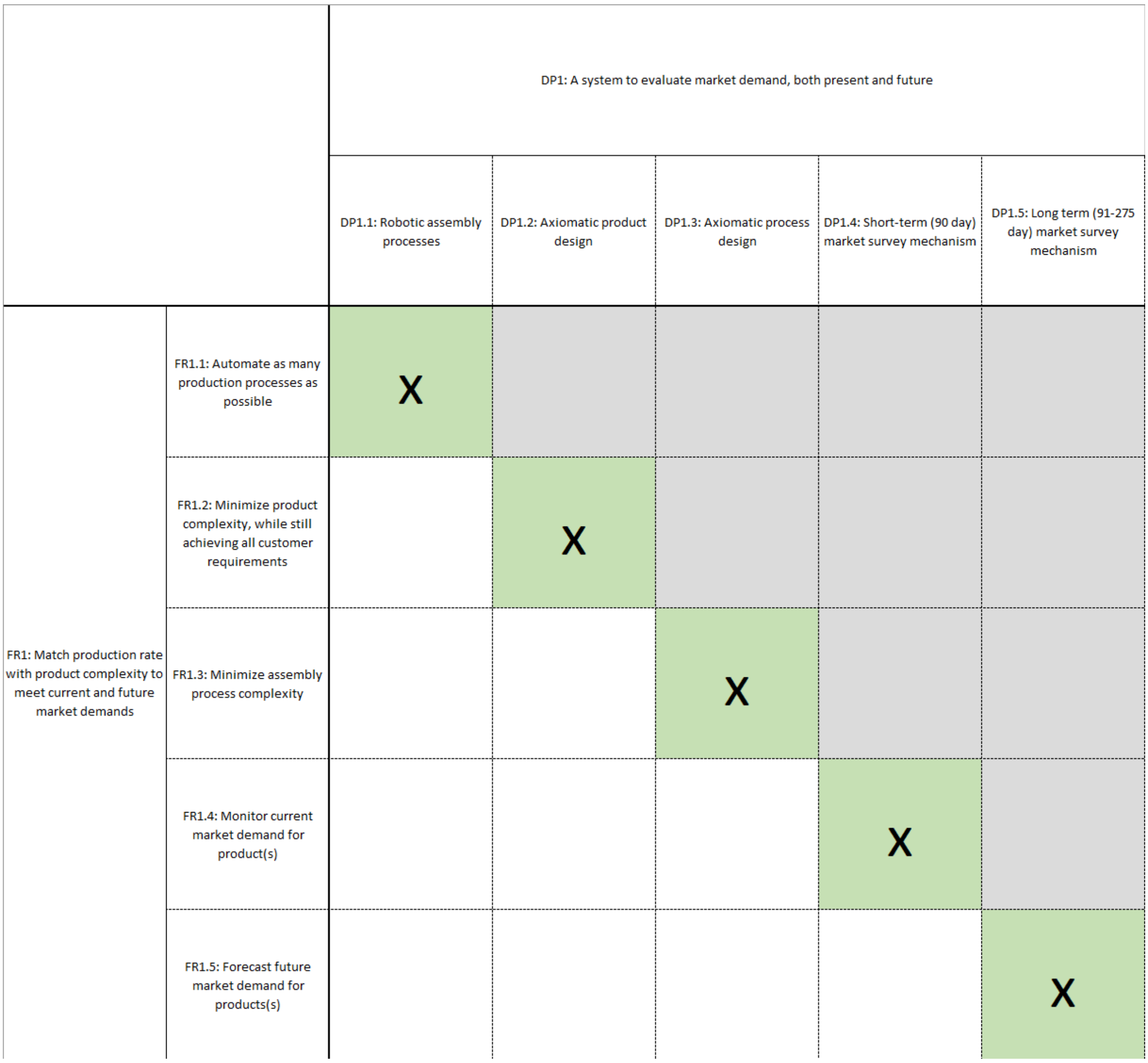
Appendices



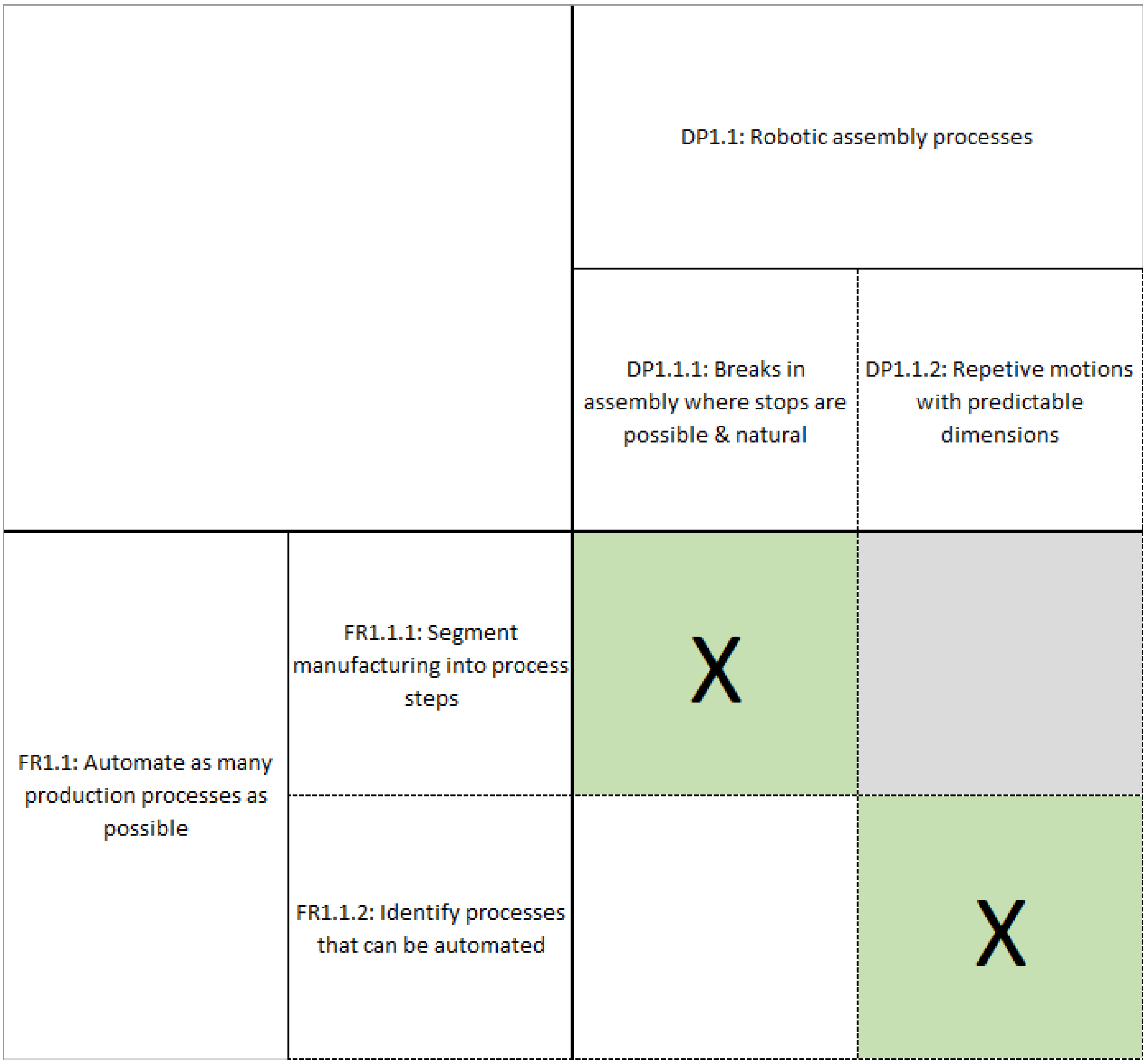
		DP0: A system that is flexible to market conditions					
		DP1: A system to evaluate market demand, both present and future	DP2: A system to evaluate products & processes for excessive complexities	DP3: An investment strategy that takes positions in the stockmarket that are inversed from material needs	DP4: A system that monitors injury occurrences, and correct root causes from the feedback	DP5: A program that actively engages with professionals - both young and experienced - and students, to maximize the bandwidth of the talent pipeline	DP6: Constant monitoring of market compensation packages, with proactive raises to match current market rates for all employees that meet or exceed performance goals.
FR0: Maximize the ratio between revenue:expenses in the factory	FR1: Match production rate with product complexity to meet current and future market demands	X					
	FR2: Minimize production cycle complexity	X	X				
	FR3: Insure against potential supply shortages			X			
	FR4: Maintain worker safety at all times				X		
	FR5: Attract the best talent available in the market					X	
	FR6: Retain the best talent available in the market						X

Figure 1: The zeroth & first levels of the axiomatic matrix for a factory utilizing automated processes



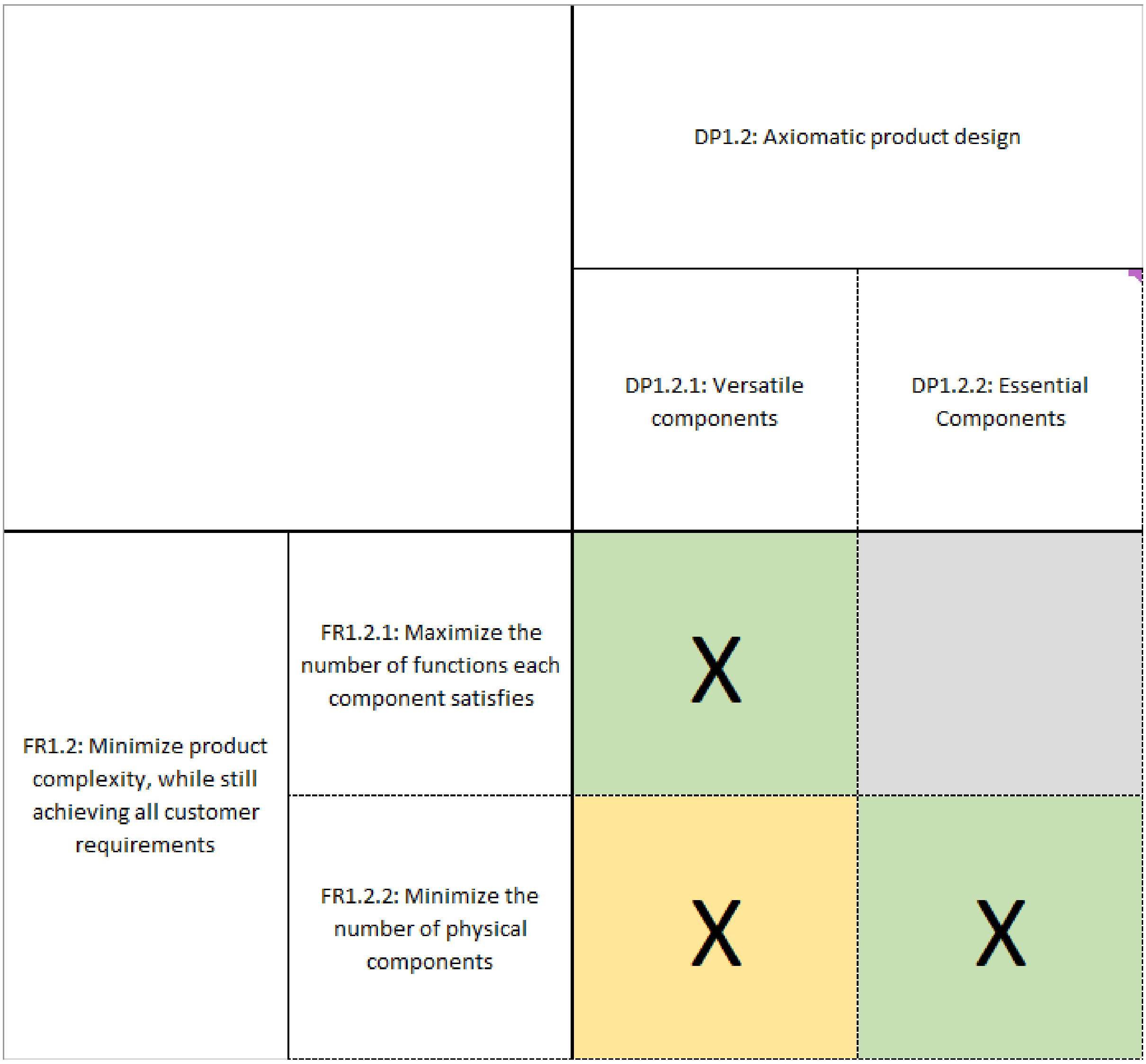
		DP1: A system to evaluate market demand, both present and future				
		DP1.1: Robotic assembly processes	DP1.2: Axiomatic product design	DP1.3: Axiomatic process design	DP1.4: Short-term (90 day) market survey mechanism	DP1.5: Long term (91-275 day) market survey mechanism
FR1: Match production rate with product complexity to meet current and future market demands	FR1.1: Automate as many production processes as possible	X				
	FR1.2: Minimize product complexity, while still achieving all customer requirements		X			
	FR1.3: Minimize assembly process complexity			X		
	FR1.4: Monitor current market demand for product(s)				X	
	FR1.5: Forecast future market demand for products(s)					X

Figure 2: FR1-DP1 Pairings



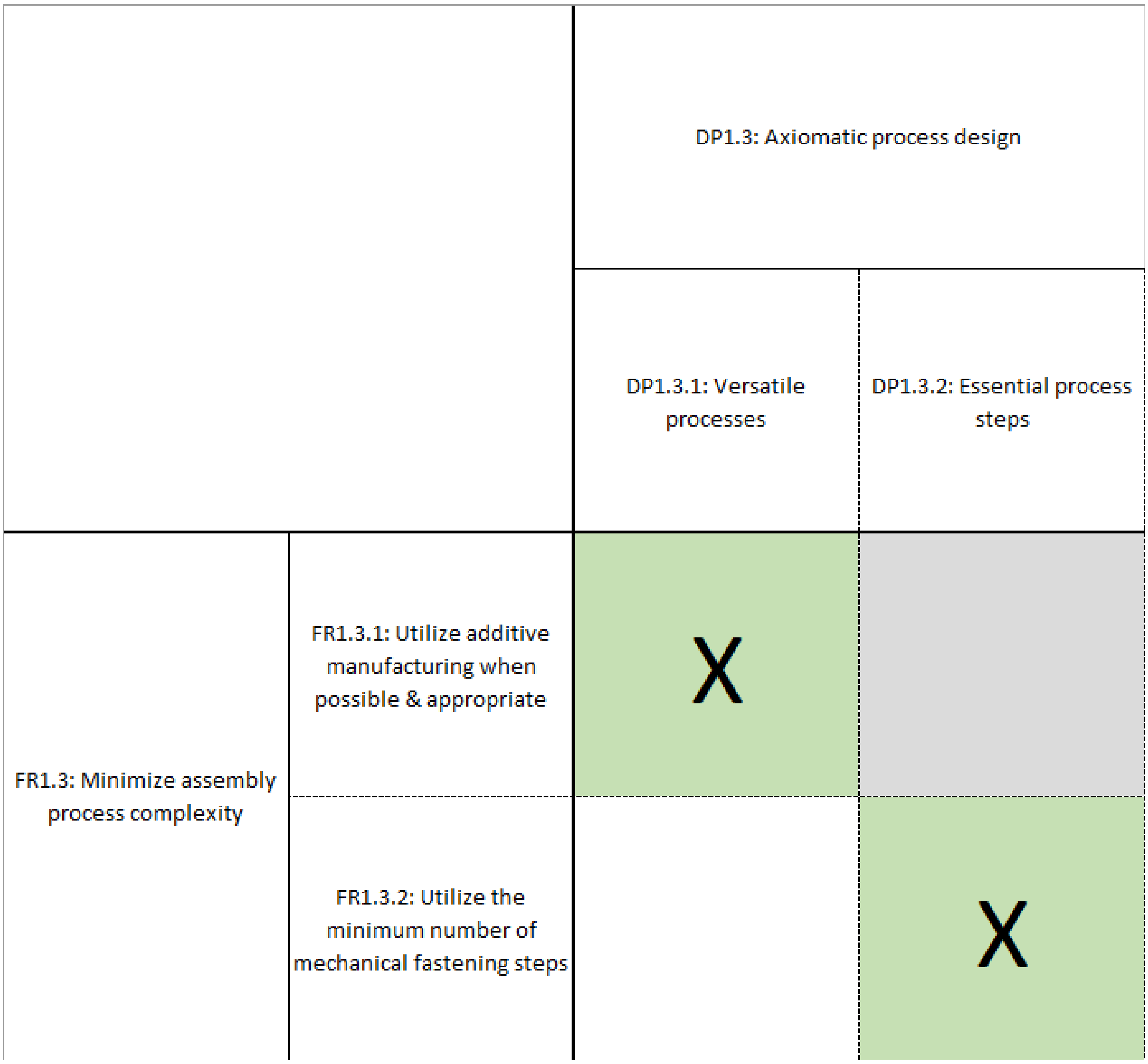
		DP1.1: Robotic assembly processes	
		DP1.1.1: Breaks in assembly where stops are possible & natural	DP1.1.2: Repetive motions with predictable dimensions
FR1.1: Automate as many production processes as possible	FR1.1.1: Segment manufacturing into process steps	X	
	FR1.1.2: Identify processes that can be automated		X

Figure 3: FR1.1-DP1.1 Pairings



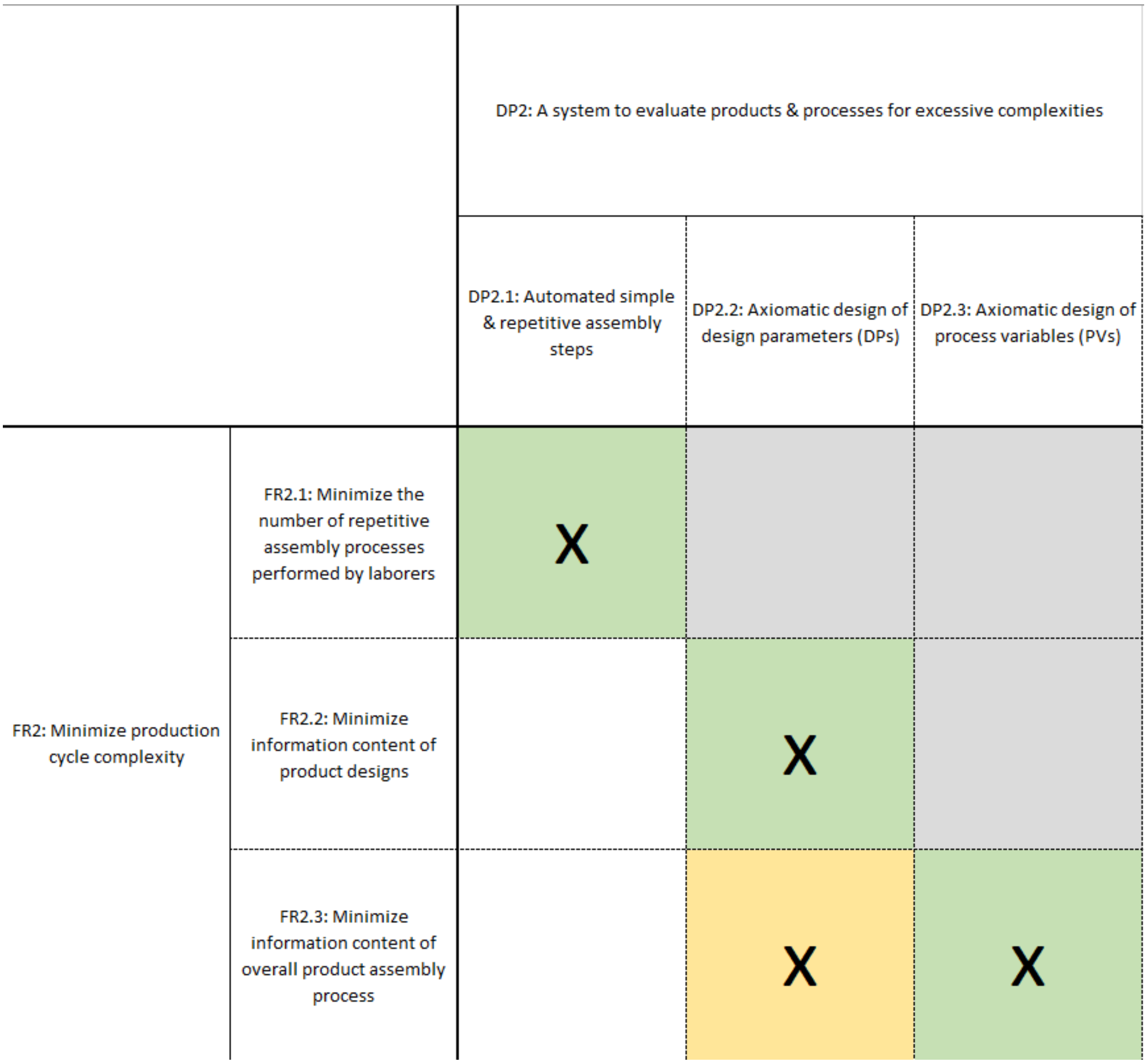
		DP1.2: Axiomatic product design	
		DP1.2.1: Versatile components	DP1.2.2: Essential Components
FR1.2: Minimize product complexity, while still achieving all customer requirements	FR1.2.1: Maximize the number of functions each component satisfies	X	
	FR1.2.2: Minimize the number of physical components	X	X

Figure 4: FR1.2-DP1.2 Pairings



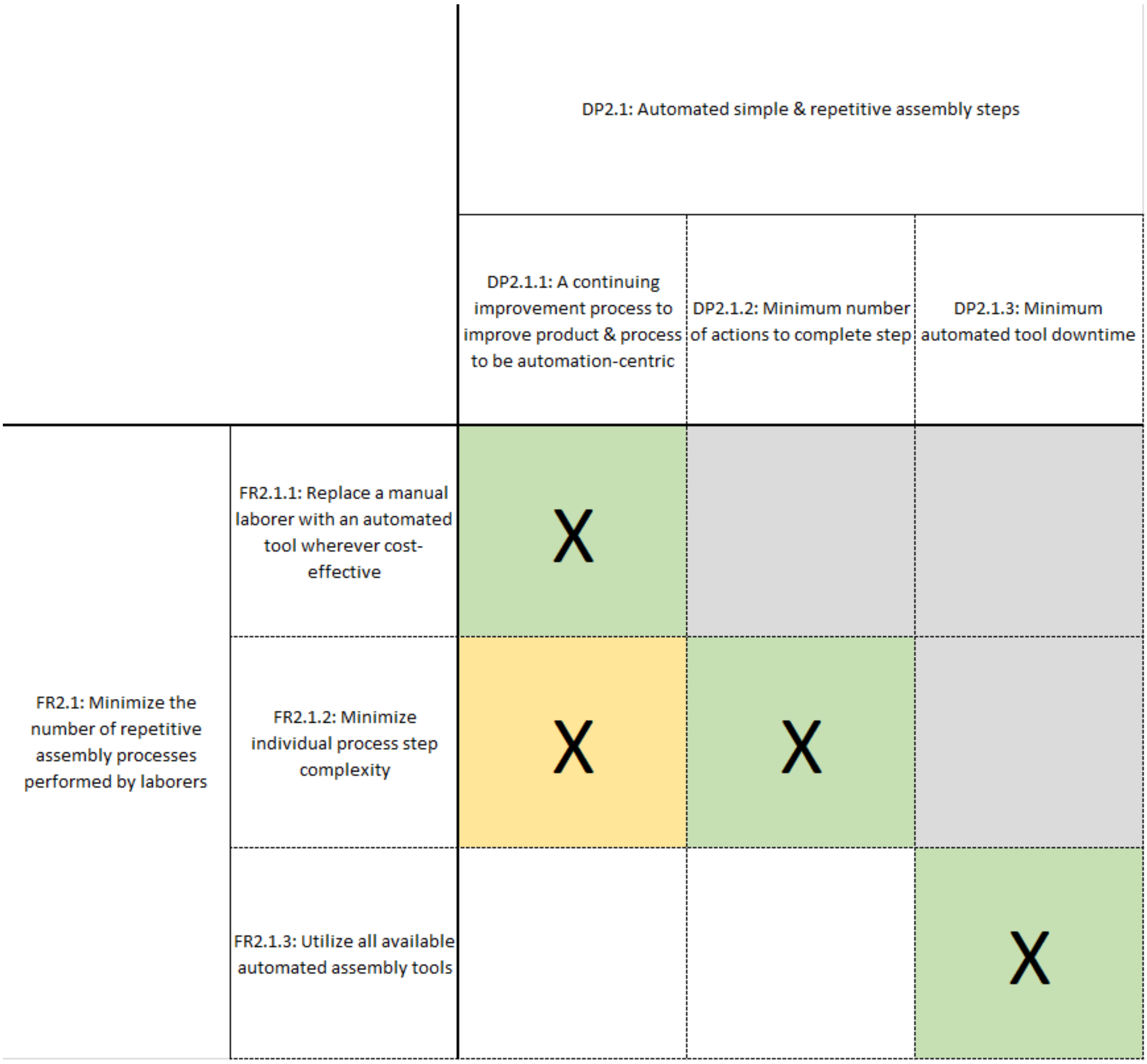
		DP1.3: Axiomatic process design	
		DP1.3.1: Versatile processes	DP1.3.2: Essential process steps
FR1.3: Minimize assembly process complexity	FR1.3.1: Utilize additive manufacturing when possible & appropriate	X	
	FR1.3.2: Utilize the minimum number of mechanical fastening steps		X

Figure 5: FR1.3-DP1.3 Pairings



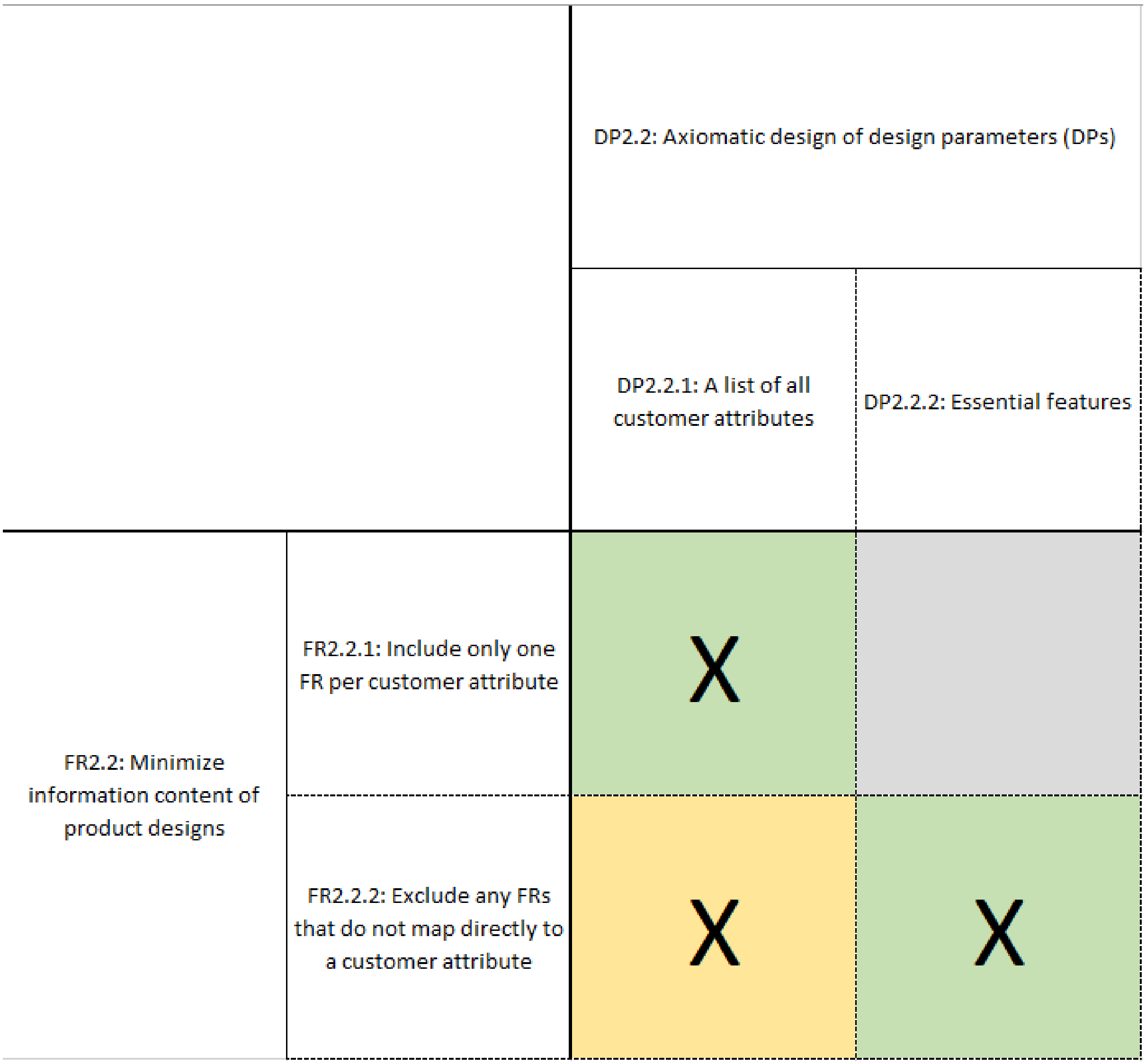
		DP2: A system to evaluate products & processes for excessive complexities		
		DP2.1: Automated simple & repetitive assembly steps	DP2.2: Axiomatic design of design parameters (DPs)	DP2.3: Axiomatic design of process variables (PVs)
FR2: Minimize production cycle complexity	FR2.1: Minimize the number of repetitive assembly processes performed by laborers	X		
	FR2.2: Minimize information content of product designs		X	
	FR2.3: Minimize information content of overall product assembly process		X	X

Figure 6: FR2-DP2 Pairings



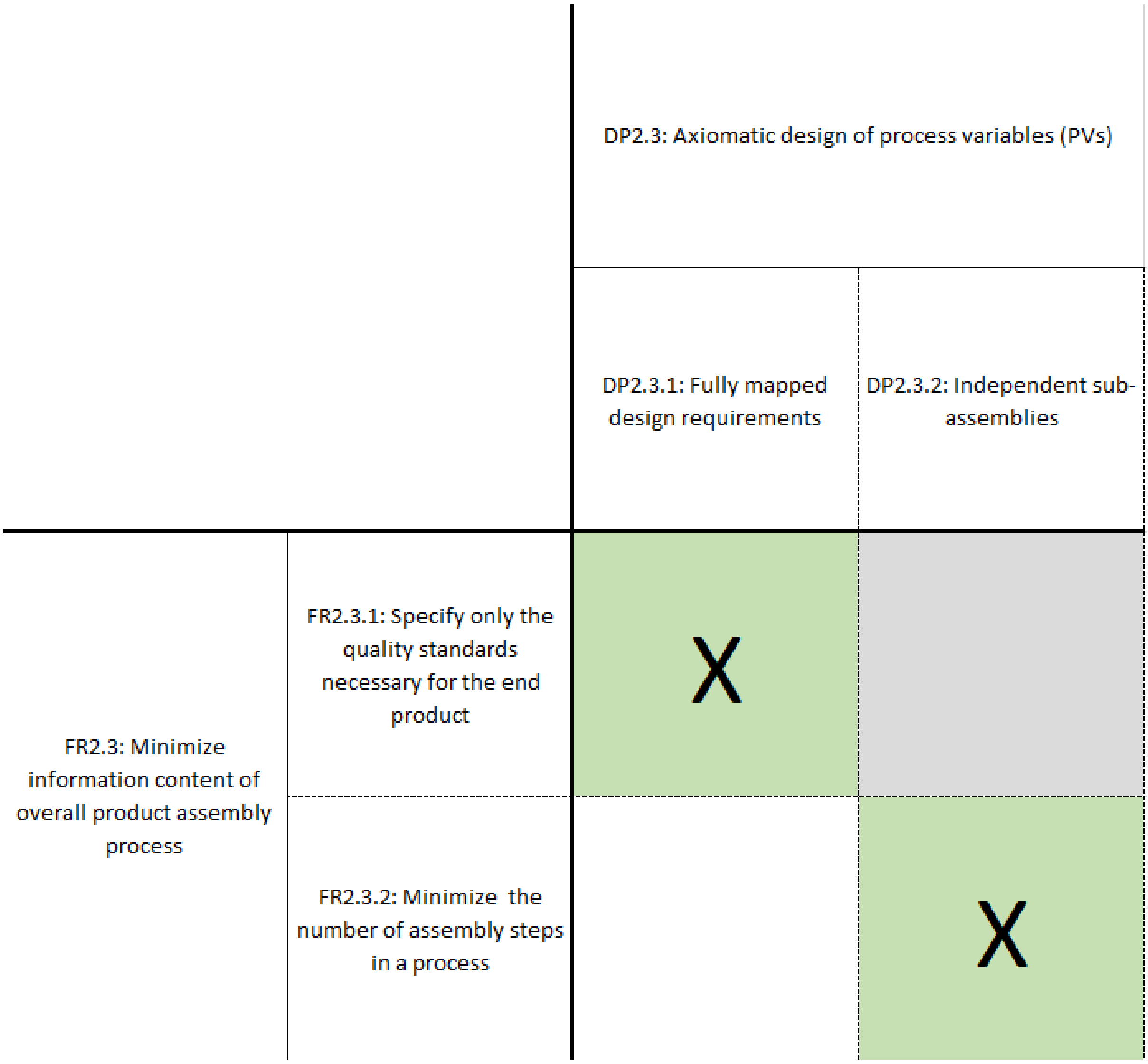
		DP2.1: Automated simple & repetitive assembly steps		
		DP2.1.1: A continuing improvement process to improve product & process to be automation-centric	DP2.1.2: Minimum number of actions to complete step	DP2.1.3: Minimum automated tool downtime
FR2.1: Minimize the number of repetitive assembly processes performed by laborers	FR2.1.1: Replace a manual laborer with an automated tool wherever cost-effective	X		
	FR2.1.2: Minimize individual process step complexity	X	X	
	FR2.1.3: Utilize all available automated assembly tools			X

Figure 7: FR2.1-DP2.1 Pairings



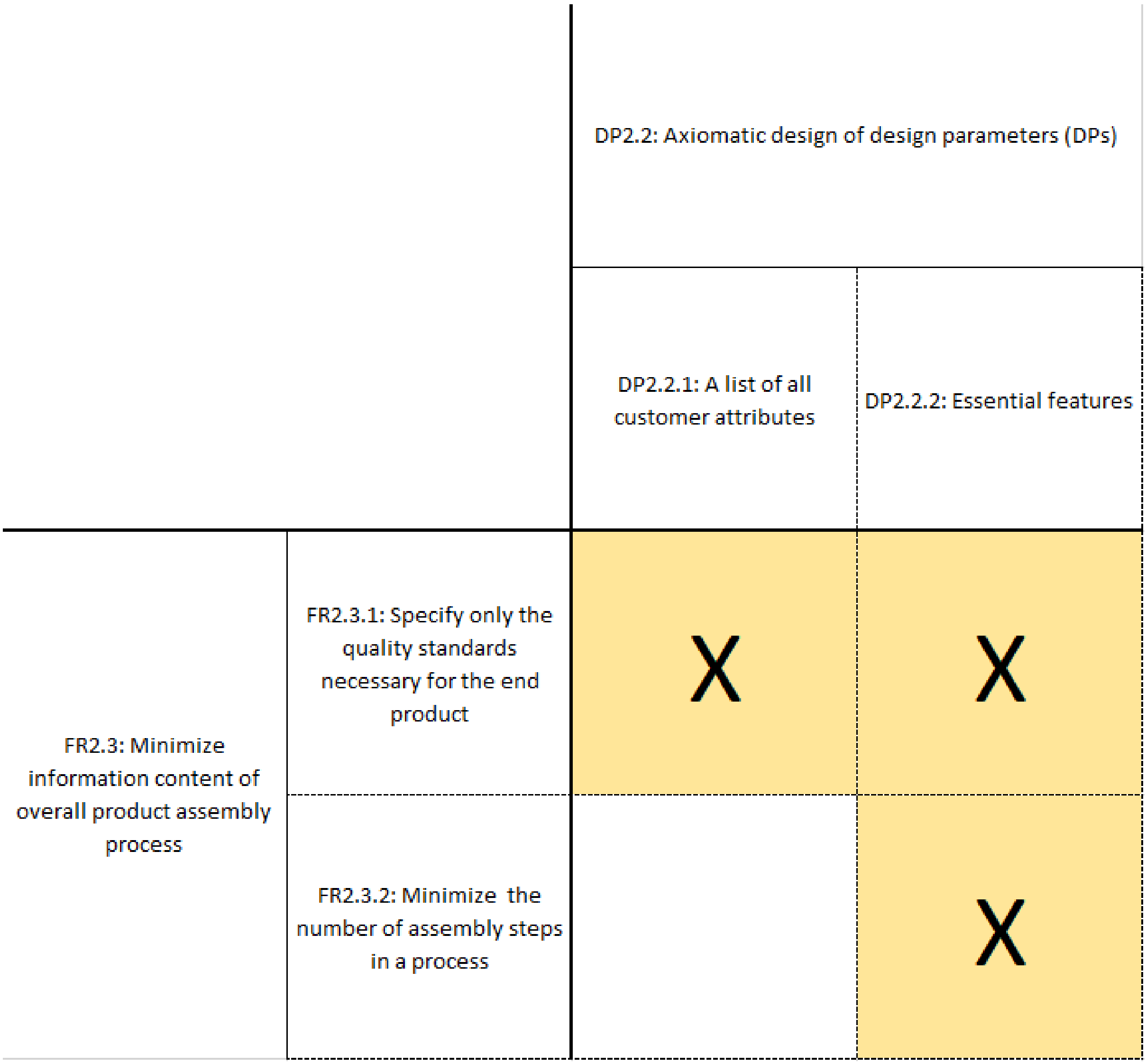
		DP2.2: Axiomatic design of design parameters (DPs)	
		DP2.2.1: A list of all customer attributes	DP2.2.2: Essential features
FR2.2: Minimize information content of product designs	FR2.2.1: Include only one FR per customer attribute	🟩 X	⬜
	FR2.2.2: Exclude any FRs that do not map directly to a customer attribute	🟨 X	🟩 X

Figure 8: FR2.2-DP2.2 Pairings



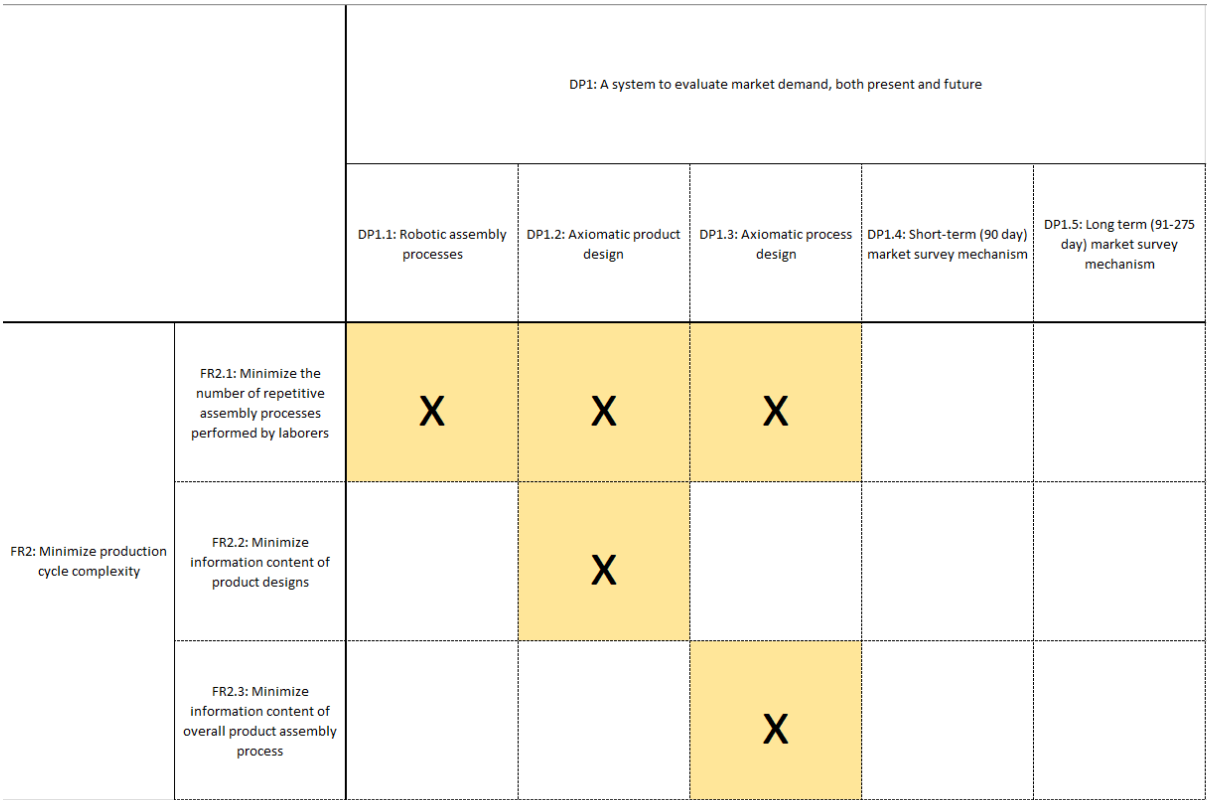
		DP2.3: Axiomatic design of process variables (PVs)	
		DP2.3.1: Fully mapped design requirements	DP2.3.2: Independent sub-assemblies
FR2.3: Minimize information content of overall product assembly process	FR2.3.1: Specify only the quality standards necessary for the end product	X	
	FR2.3.2: Minimize the number of assembly steps in a process		X

Figure 9: FR2.3-DP2.3 Pairings



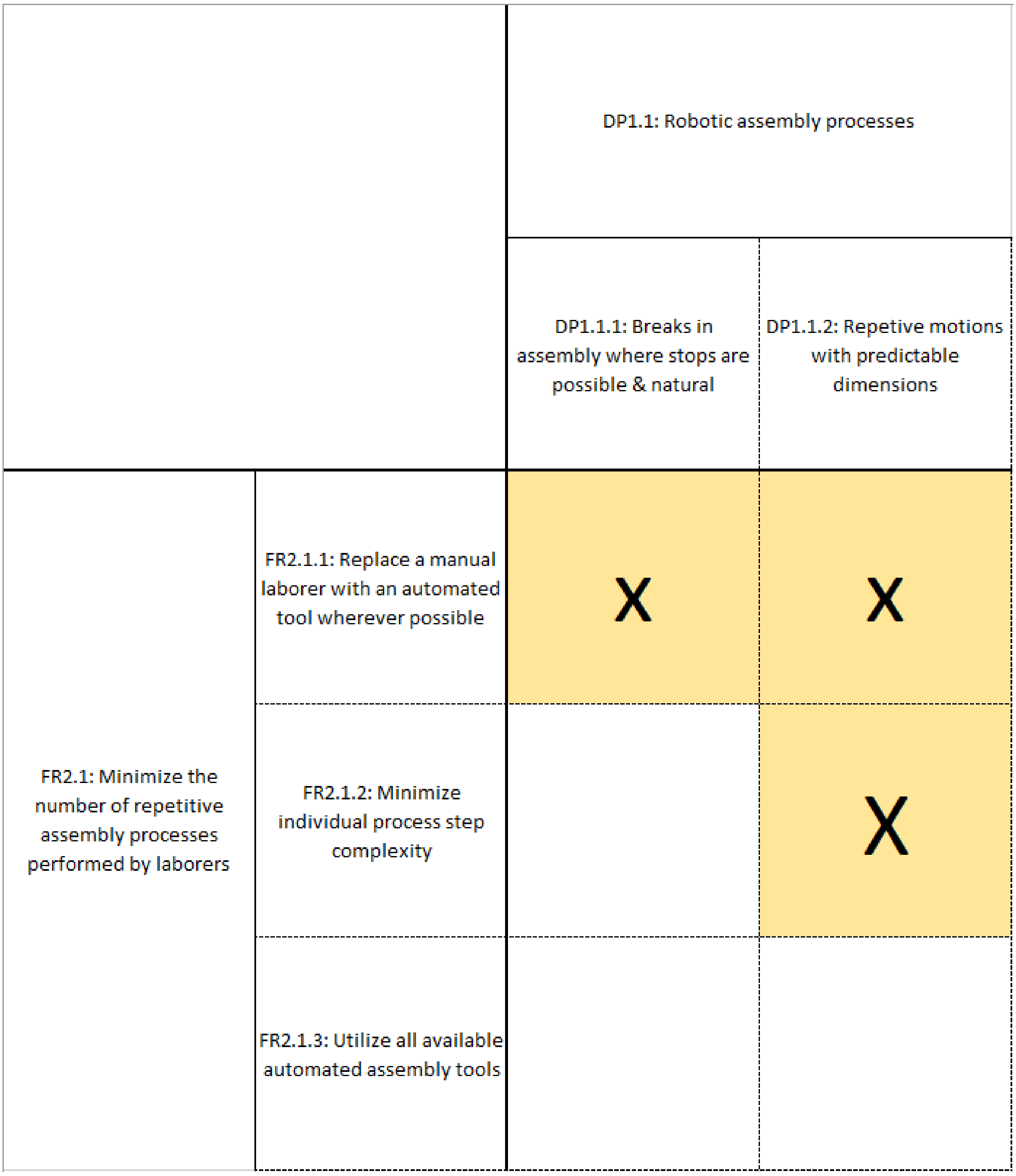
		DP2.2: Axiomatic design of design parameters (DPs)	
		DP2.2.1: A list of all customer attributes	DP2.2.2: Essential features
FR2.3: Minimize information content of overall product assembly process	FR2.3.1: Specify only the quality standards necessary for the end product	X	X
	FR2.3.2: Minimize the number of assembly steps in a process		X

Figure 10: FR2.3-DP2.2 Pairings



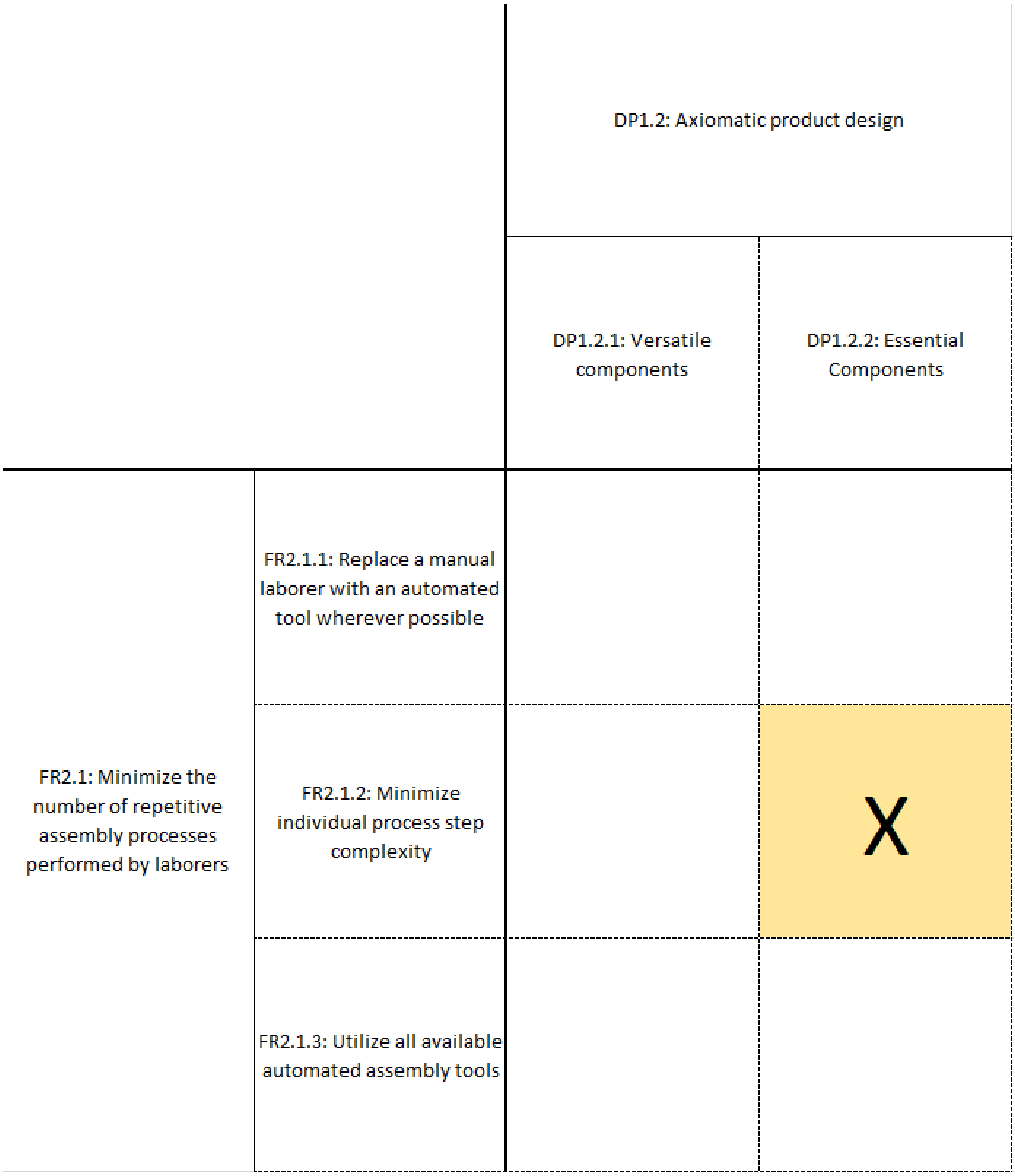
		DP1: A system to evaluate market demand, both present and future				
		DP1.1: Robotic assembly processes	DP1.2: Axiomatic product design	DP1.3: Axiomatic process design	DP1.4: Short-term (90 day) market survey mechanism	DP1.5: Long term (91-275 day) market survey mechanism
FR2: Minimize production cycle complexity	FR2.1: Minimize the number of repetitive assembly processes performed by laborers	X	X	X		
	FR2.2: Minimize information content of product designs		X			
	FR2.3: Minimize information content of overall product assembly process			X		

Figure 11: FR2-DP1 Pairings



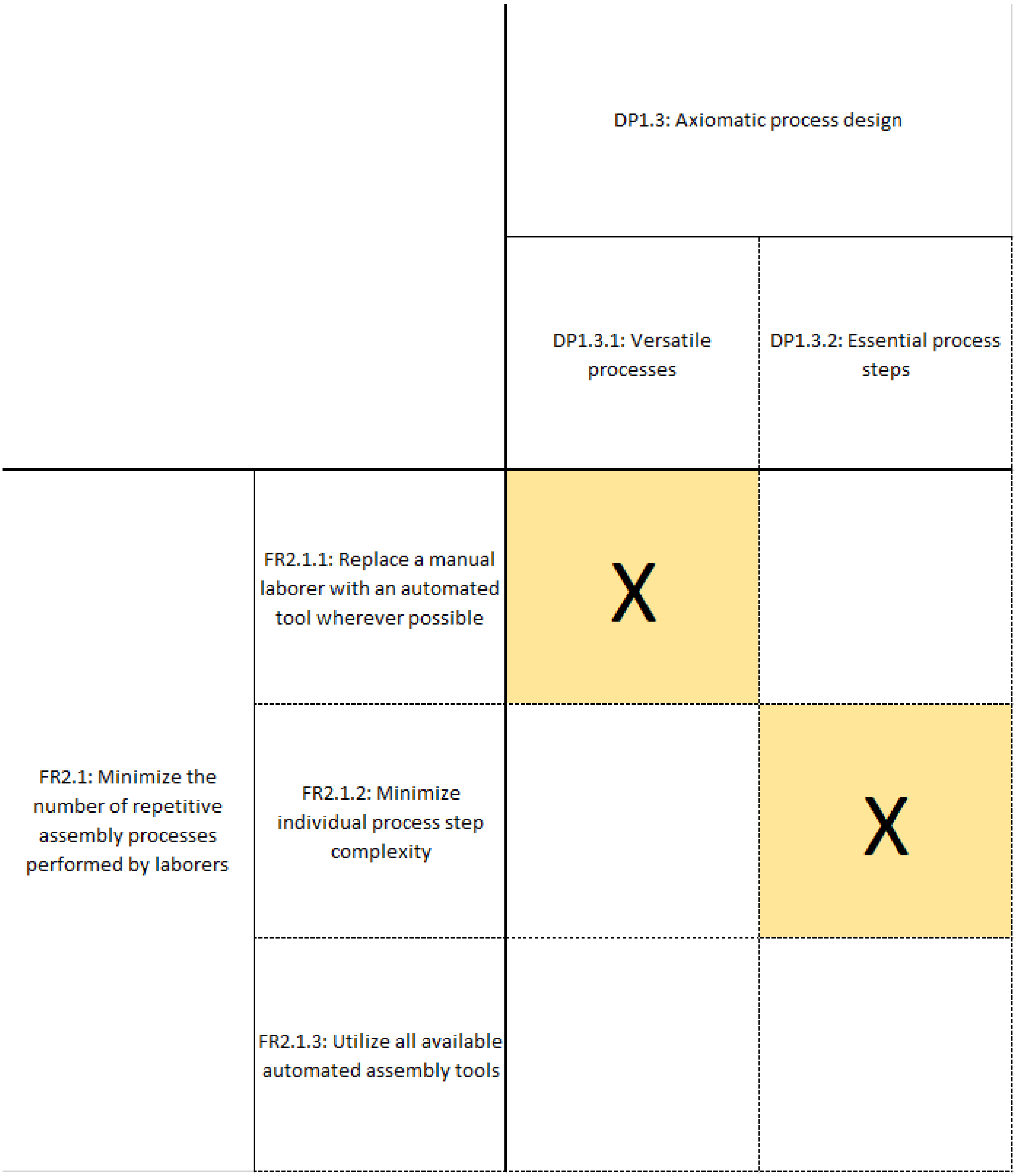
		DP1.1: Robotic assembly processes	
		DP1.1.1: Breaks in assembly where stops are possible & natural	DP1.1.2: Repetive motions with predictable dimensions
FR2.1: Minimize the number of repetitive assembly processes performed by laborers	FR2.1.1: Replace a manual laborer with an automated tool wherever possible	X	X
	FR2.1.2: Minimize individual process step complexity		X
	FR2.1.3: Utilize all available automated assembly tools		

Figure 12: FR2.1-DP1.1 Pairings



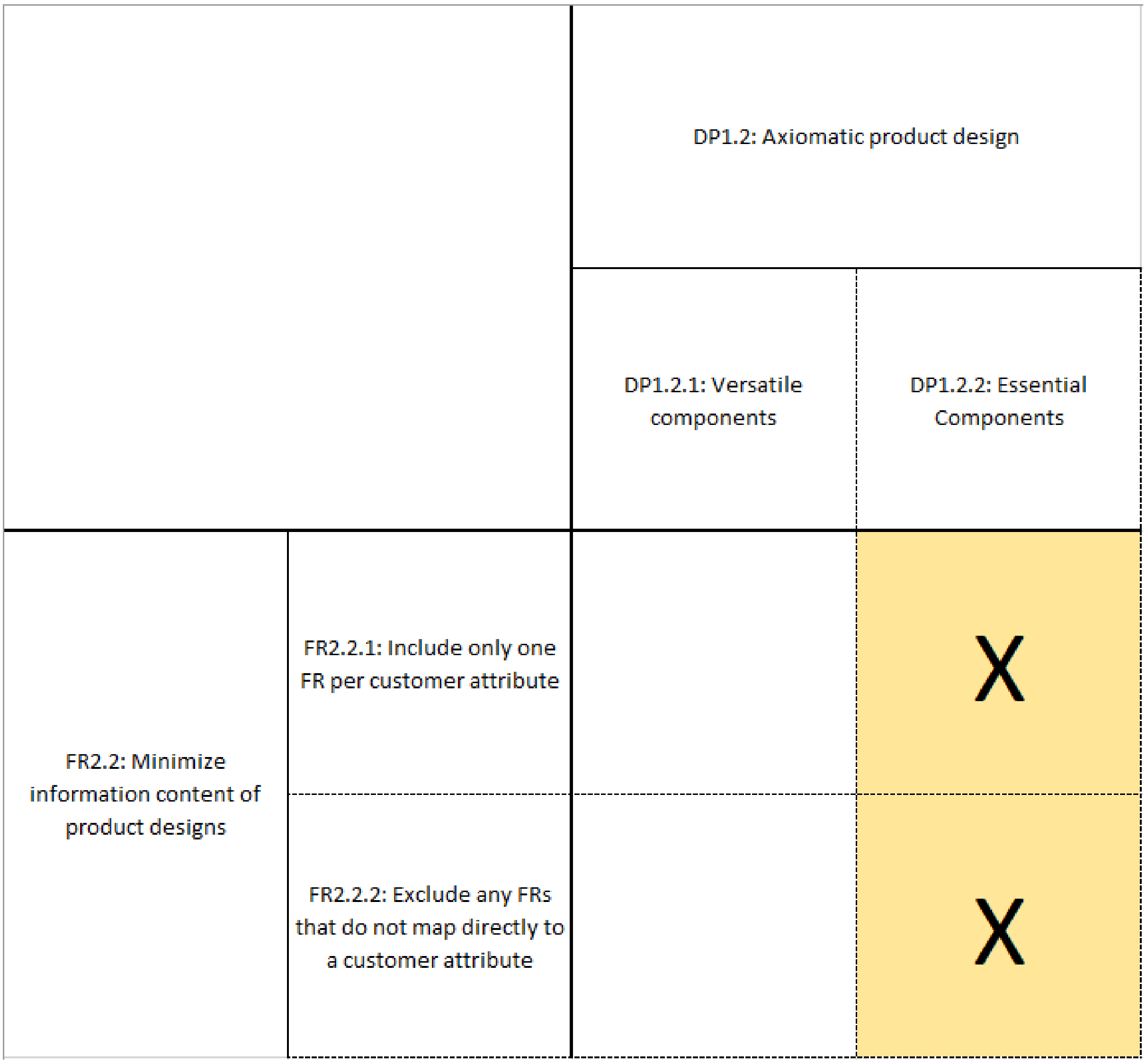
		DP1.2: Axiomatic product design	
		DP1.2.1: Versatile components	DP1.2.2: Essential Components
FR2.1: Minimize the number of repetitive assembly processes performed by laborers	FR2.1.1: Replace a manual laborer with an automated tool wherever possible		
	FR2.1.2: Minimize individual process step complexity		X
	FR2.1.3: Utilize all available automated assembly tools		

Figure 13: FR2.1-DP1.2 Pairings



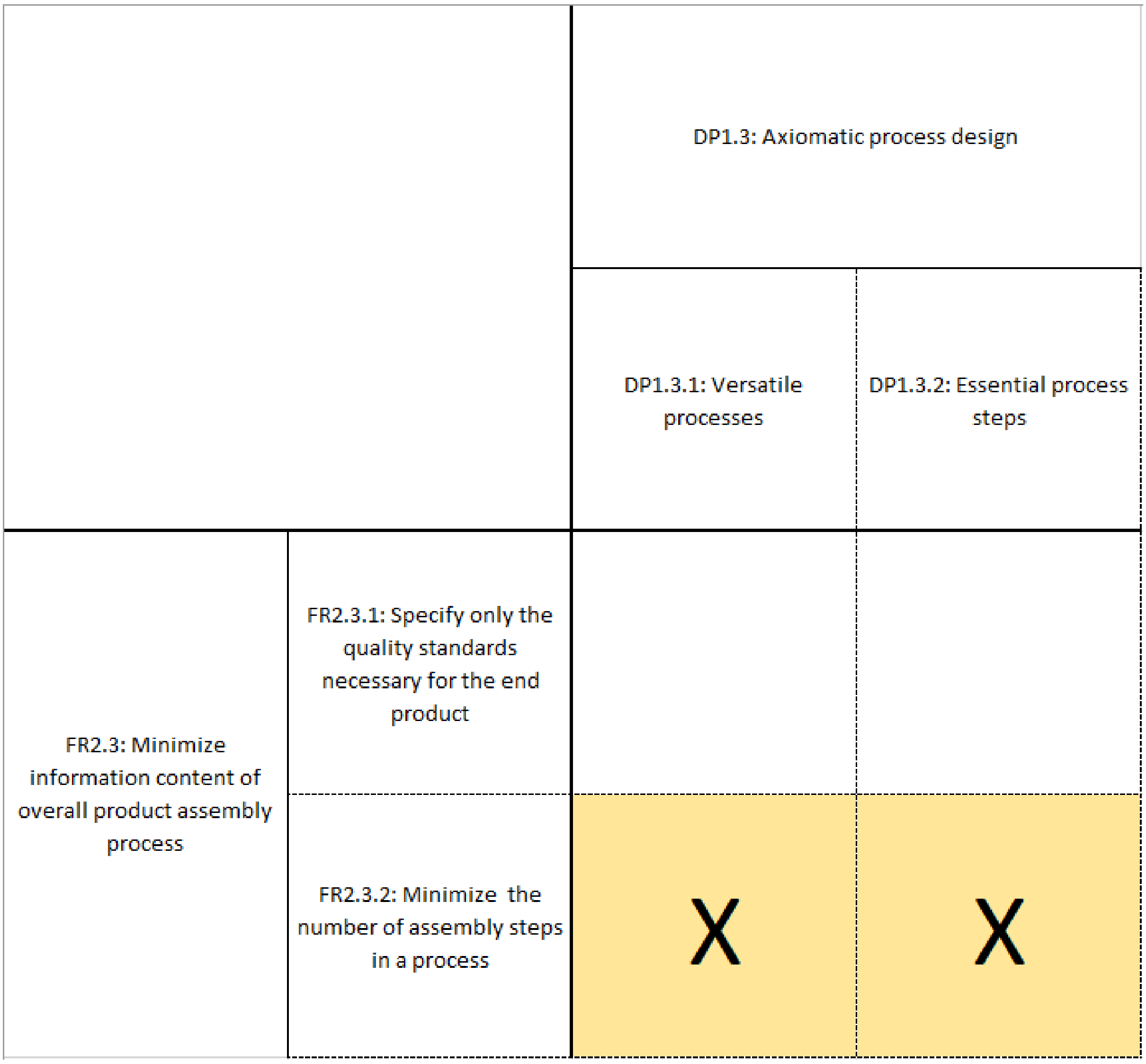
		DP1.3: Axiomatic process design	
		DP1.3.1: Versatile processes	DP1.3.2: Essential process steps
FR2.1: Minimize the number of repetitive assembly processes performed by laborers	FR2.1.1: Replace a manual laborer with an automated tool wherever possible	X	
	FR2.1.2: Minimize individual process step complexity		X
	FR2.1.3: Utilize all available automated assembly tools		

Figure 14: FR2.1-DP1.3 Pairings



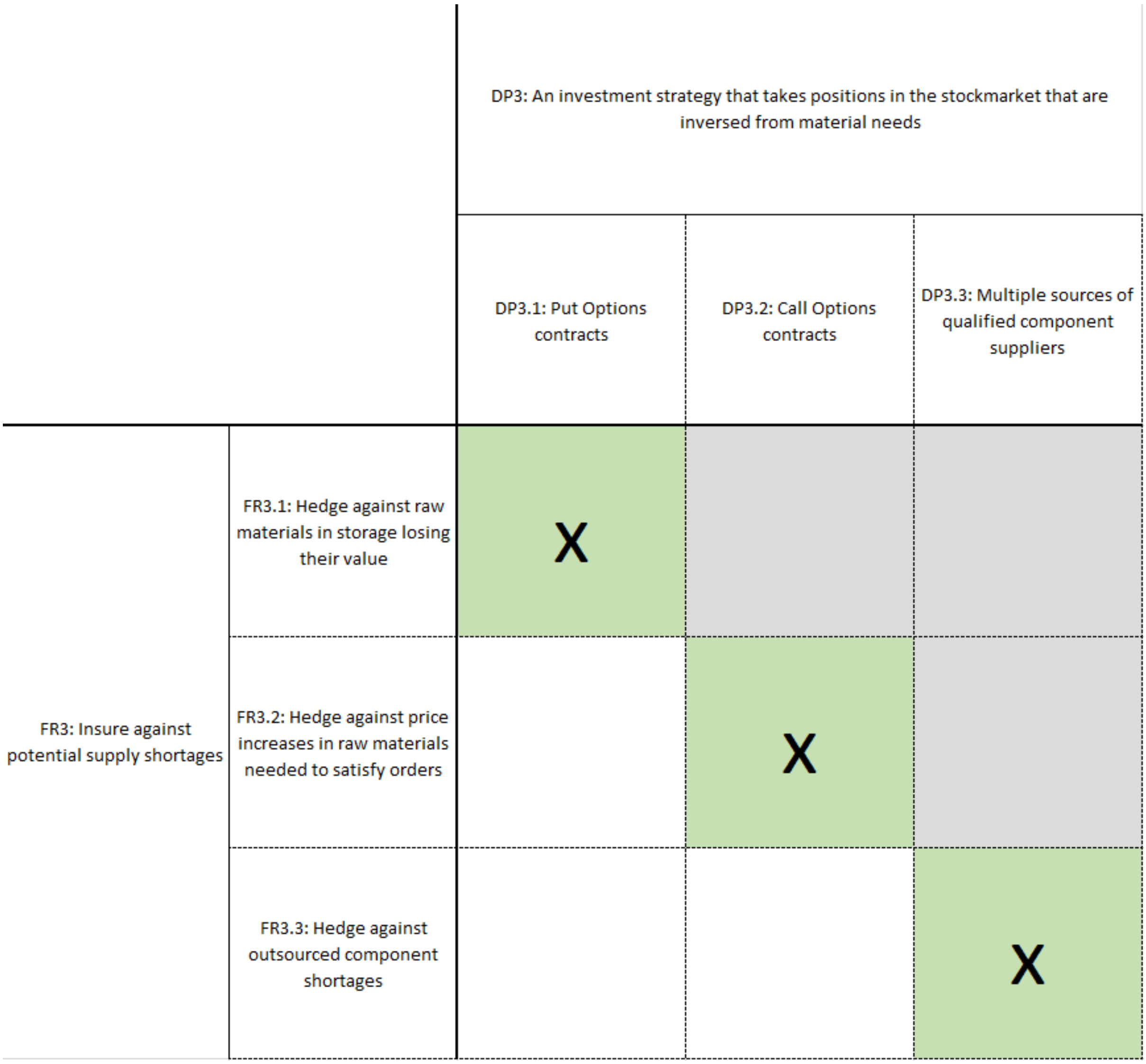
		DP1.2: Axiomatic product design	
		DP1.2.1: Versatile components	DP1.2.2: Essential Components
FR2.2: Minimize information content of product designs	FR2.2.1: Include only one FR per customer attribute		X
	FR2.2.2: Exclude any FRs that do not map directly to a customer attribute		X

Figure 15: FR2.2-DP1.2 Pairings



		DP1.3: Axiomatic process design	
		DP1.3.1: Versatile processes	DP1.3.2: Essential process steps
FR2.3: Minimize information content of overall product assembly process	FR2.3.1: Specify only the quality standards necessary for the end product		
	FR2.3.2: Minimize the number of assembly steps in a process	X	X

Figure 16: FR2.3-DP1.3 Pairings

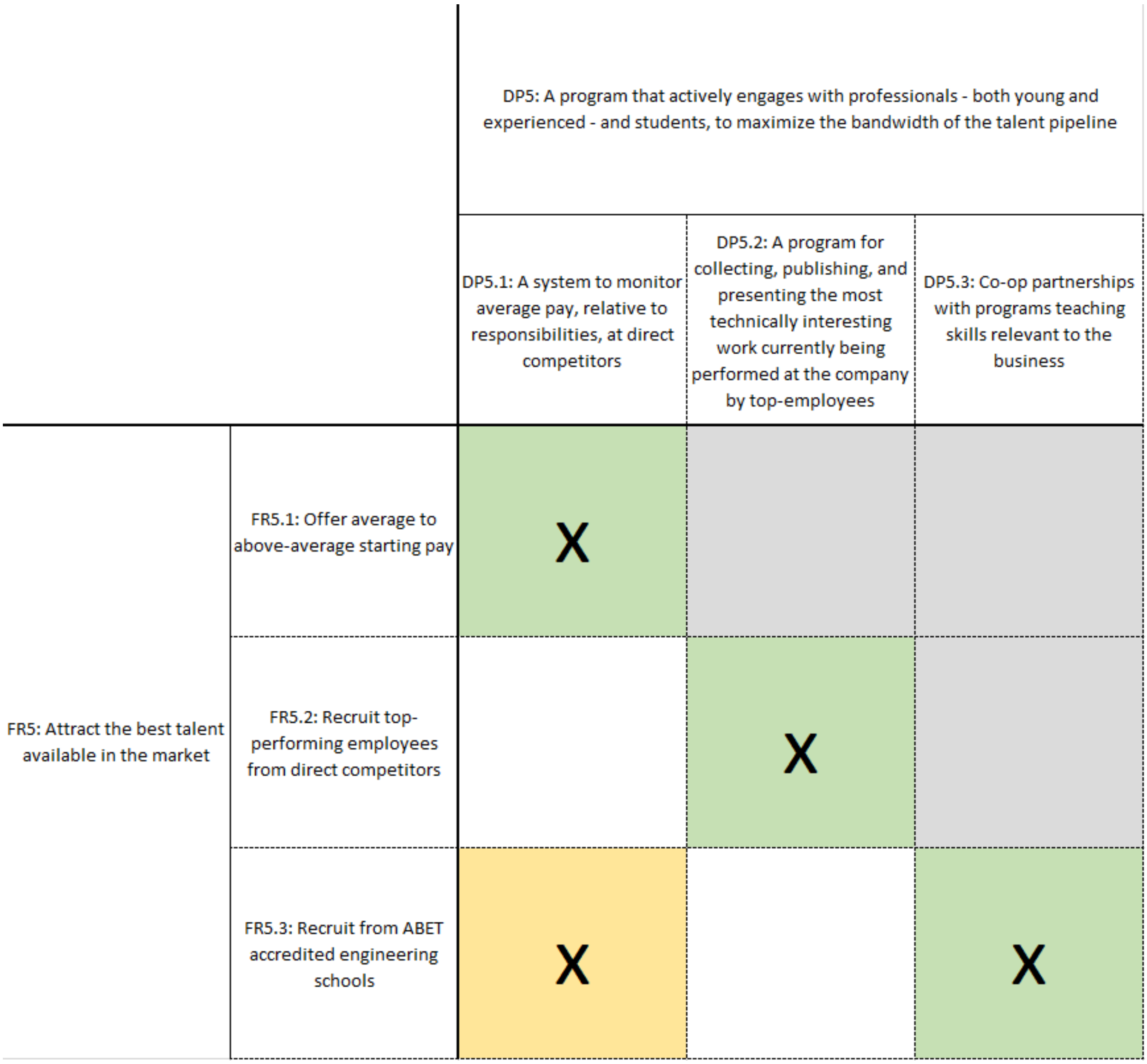


		DP3: An investment strategy that takes positions in the stockmarket that are inversed from material needs		
		DP3.1: Put Options contracts	DP3.2: Call Options contracts	DP3.3: Multiple sources of qualified component suppliers
FR3: Insure against potential supply shortages	FR3.1: Hedge against raw materials in storage losing their value	X		
	FR3.2: Hedge against price increases in raw materials needed to satisfy orders		X	
	FR3.3: Hedge against outsourced component shortages			X

Figure 17: FR3-DP3 Pairings

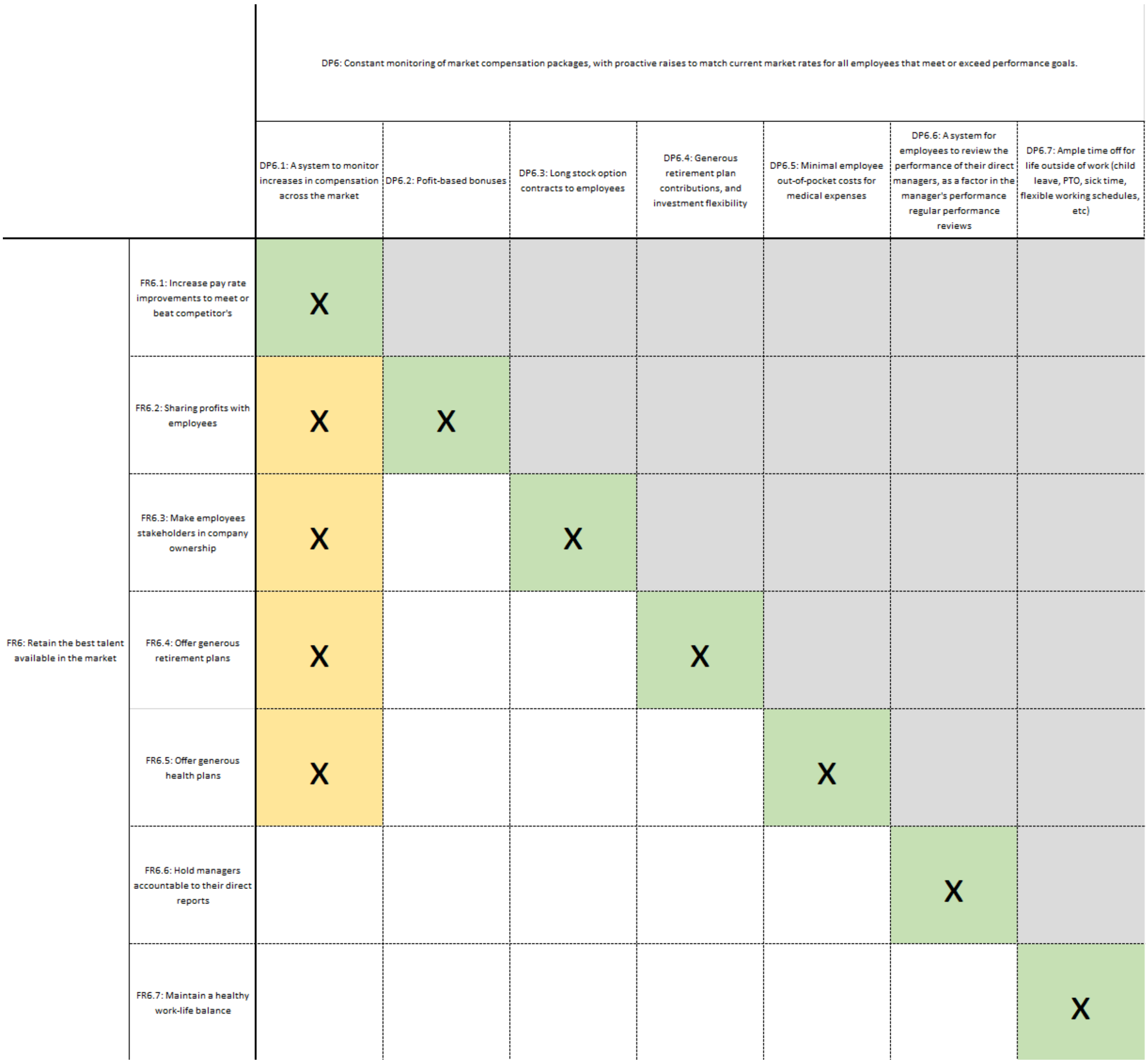
		DP4: A system that monitors injury occurrences, and correct root causes from the feedback					
		DP4.1: A consequence-free, injury reporting tool (reactive safety)	DP4.2: An independent accident & safety investigation team	DP4.3: A tool for consistently logging data about accidents	DP4.4: A tool for feeding back safety data to process designers	DP4.5: A system for disseminating statistics about safety & accident trends, and safe work practices	DP4.6: A consequence-free safety-concern reporting tool (proactive safety)
FR4: Maintain worker safety at all times	FR4.1: Capture all instances of recordable injuries	X					
	FR4.2: Determine root cause of recordable injuries		X				
	FR4.3: Track injury rates relative to production areas			X			
	FR4.4: Track injury rates relative to production tasks			X	X		
	FR4.5: Make feedback about injury data available to all employees					X	
	FR4.6: Create a system for anonymously and privately reporting safety concerns		X				X

Figure 18: FR4-DP4 Pairings



		DP5: A program that actively engages with professionals - both young and experienced - and students, to maximize the bandwidth of the talent pipeline		
		DP5.1: A system to monitor average pay, relative to responsibilities, at direct competitors	DP5.2: A program for collecting, publishing, and presenting the most technically interesting work currently being performed at the company by top-employees	DP5.3: Co-op partnerships with programs teaching skills relevant to the business
FR5: Attract the best talent available in the market	FR5.1: Offer average to above-average starting pay	X		
	FR5.2: Recruit top-performing employees from direct competitors		X	
	FR5.3: Recruit from ABET accredited engineering schools	X		X

Figure 19: FR5-DP5 Pairings



		DP6: Constant monitoring of market compensation packages, with proactive raises to match current market rates for all employees that meet or exceed performance goals.						
		DP6.1: A system to monitor increases in compensation across the market	DP6.2: Pofit-based bonuses	DP6.3: Long stock option contracts to employees	DP6.4: Generous retirement plan contributions, and investment flexibility	DP6.5: Minimal employee out-of-pocket costs for medical expenses	DP6.6: A system for employees to review the performance of their direct managers, as a factor in the manager's performance regular performance reviews	DP6.7: Ample time off for life outside of work (child leave, PTO, sick time, flexible working schedules, etc)
FR6: Retain the best talent available in the market	FR6.1: Increase pay rate improvements to meet or beat competitor's	X						
	FR6.2: Sharing profits with employees	X	X					
	FR6.3: Make employees stakeholders in company ownership	X		X				
	FR6.4: Offer generous retirement plans	X			X			
	FR6.5: Offer generous health plans	X				X		
	FR6.6: Hold managers accountable to their direct reports						X	
	FR6.7: Maintain a healthy work-life balance							X

Figure 20: FR6-DP6 Pairings