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Evaluating compatibility between machines and operations for aerospace engine products

Master's thesis in Production Engineering

ROBERTO COSTANZO
VEDANTH LIMBAYYASWAMIMATH

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE
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VEDANTH LIMBAYYASWAMIMATH

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VEDANTH LIMBAYYASWAMIMATH

Academic examiner and supervisor: Kristina Wärmefjord, Department of Industrial and Materials Science
Academic co-supervisor: Sunney Fotedar, Department of Mathematical Sciences
GKN Aerospace supervisor: Stefan Cedergren, Process Engineer

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Department of Industrial and Materials Science
Production Engineering Master's programme
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Chiara Costanzo

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ROBERTO COSTANZO
VEDANTH LIMBAYYASWAMIMATH
Department of of Industrial and Materials Science
Chalmers University of Technology

Abstract

Purpose - In today's globalized marketplace, businesses of all kinds experience a constant change in customer needs and demands. For a company to stay competitive, it is essential to have flexible production systems, which allow for rapid production changes and ensure that new products are effectively and quickly introduced into the factory. Before a new product, or a change in product specifications, is introduced into the production system, two main areas must be carefully evaluated, i.e., the identification of the critical features of the product and the identification of suitable machines to perform the required machining operations. The main aim of the project is the development of a model based on the evaluation of those two areas for identifying the critical parameters that have a direct effect on resource allocation at GKN Aerospace.

Methodology - A triangulation of methods was used. A literature review was conducted to get an overview of the research area. Quantitative and qualitative data were retrieved from GKN Aerospace and analyzed to comprehensively investigate the area of study.

Findings - The products and machines of interest were assessed for identifying the critical parameters that have a direct impact on resource allocation. These results were then used to analyze the associations between product features and machine capabilities to develop a model that can help in implementing effective resource allocation strategies at GKN Aerospace. Specifically, two products and about forty machines were used to test the model. Recommendations were also provided on how to improve and make the implementation of the association model more effective and responsive.

Limitations - The research was limited to only the machines capable of performing certain cutting operations (turning, milling and drilling) and to only three products. The project does not include any software development to automate the association procedure between product features and machine capabilities. Moreover, due to the inaccuracy of some data (which in some cases were generalized for the purpose of running the model), the results of the association matrices may not be accurate. Furthermore, due to time constraints and lack of data, the model could only be tested for two of the three products studied.

Keywords: resource allocation, production system, product features, machine capabilities, aerospace, standardization, geometry assurance, statistical quality control, sustainability.

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Roberto Costanzo, Vedanth Limbayyaswamimath, Gothenburg, May 2021

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List of Abbreviations

ACAPP - Automatic Computer-Aided Process Planning
AFR - Automatic Feature Recognition
ANSI - American National Standards Institute
CAD - Computer-Aided Design
CAM - Computer-Aided Manufacturing
CAPP - Computer-Aided Process Planning
CAT - Computer Aided Tolerancing
CNC - Computerized Numerical Control
DFC - Datum Flow Chain
DMSC - Digital Metrology Standards Consortium
FMS - Flexible Manufacturing System
HPC - High-Pressure Compressor
HPT - High-Pressure Turbine
ICC - Intermediate Compressor Case
ID - Inside Diameter
IMC - Intermediate Case
IPC - Intermediate-Pressure Compressor
IPT - Intermediate-Pressure Turbine
ISO - International Organization for Standardization
JSON - JavaScript Object Notation
KC - Key Characteristic
KMC - Key Machine Capability
KPF - Key Product Feature
LPC - Low-Pressure Compressor
LPT - Low-Pressure Turbine
LSL - Lower Specification Limit
NC - Numerical Control
PMI - Product and Manufacturing Information
QIF - Quality Information Framework
RMS - Reconfigurable Manufacturing System
RQ - Research question
SI-AFR - Smart Interactive Automatic Feature Recognition
STEP - STandard for the Exchange of Product data
TBH - Tail Bearing Housing
TBL - Triple Bottom Line
TEC - Turbine Exhaust Case
TRF - Turbine Rear Frame

USL - Upper Specification Limit
WCED - World Commission on Environment and Development

1

Introduction

In the following chapter, the background of this project and the project itself are described. The project's research questions, purpose, objectives and delimitation are also included.

1.1 Background

In today's globalized marketplace, businesses of all kinds experience a constant change in customer needs and demands. For a company to stay competitive, it is essential to have flexible production systems, which allow for rapid production changes and ensure that new products are effectively and quickly introduced into the factory (AlGeddawy & ElMaraghy, 2010). Before a new product, or a change in product specifications, is introduced into the production system, two main areas must be carefully evaluated, i.e., the identification of the critical features of the product and the identification of the machines suitable for performing the machining operations required for that product (Fotedar et al., 2019). Nonetheless, a separate study of these two areas is not sufficient to guarantee a satisfactory result of the production system. The two areas need to be analyzed in relation to each other (AlGeddawy & ElMaraghy, 2010). Based on the assessment of the relationship between product features and machine capabilities, efficient production plans can be identified, suitable for effectively managing changes in production.

In general, the aerospace industry presents a large variety of products, but with low production volumes (Fotedar et al., 2019). This has forced production systems to make use of existing resources more systematically, so that their allocation ensures to meet the future demand and new requirements (Fotedar et al., 2019). The introduction of a new product is closely related to the production system and its capability to withstand changes and to the ability to effectively allocate resources (Fotedar et al., 2020).

1.2 GKN Aerospace

GKN Aerospace Engine Systems in Trollhättan (Sweden) is part of GKN Aerospace, a leading global supplier of aircraft components such as jet engines, aircraft structures, cabin windows, cabling, and other specific products. The company has a presence in 41 manufacturing locations in 13 countries around the world (GKN Aerospace 1, 2021). In Trollhättan, GKN Aerospace develops and manufactures aircraft engines, advanced components for the turbine and compressor sections of the engine and space rockets (GKN Aerospace 2, 2021).

1.2.1 Resource allocation at GKN Aerospace

Tactical resource allocation is a comprehensive approach aimed at identifying which production processes need to be developed over the medium- to long-term planning horizon. GKN Aerospace encounters difficulties in allocating manufacturing resources in a balanced and effective way due to the following reasons (Fotedar et al., 2019):

- The organization of their work environment in functional oriented shops, which are notoriously fixed and inflexible configurations.
- High-quality standards to comply with, mainly requested by GKN Aerospace's customers. Even slight deviations from the tolerance range result in immediate production stops and rework.
- Shared resources among multiple products/parts.
- Complex and time-consuming process planning when it comes to introducing new products into the factory.
- Low volumes, many product variants and uncertain demand.

The result is a high-capacity load on the most capable machines (preferred as they minimize the total time that products require to be machined) and a very low-capacity load on less capable resources (Fotedar et al., 2019). This generates profound imbalances between machines, long queues, increased lead times and consequently high costs (Fotedar et al., 2019).

GKN Aerospace, as the whole aerospace industry, manufactures an enormous amount of product variants, with different design and mechanical specifications. Furthermore, the company has a large number of resources to select from. As a result, when it is necessary to introduce new products into their production system, selecting the right resources is an intricate operation (Fotedar et al., 2019). Hence, it is crucial to understand how product features and machine capabilities relate to each other and how this relationship can be used to effectively allocate resources. Furthermore, since frequent changes in production are common, an approach to effectively address this need should also be implemented (AlGeddawy & ElMaraghy, 2010).

1.2.2 Sustainability at GKN Aerospace

At GKN Aerospace, sustainability is a core commitment (GKN Aerospace 3, 2021). They define their approach to sustainability as "doing the right thing – by our people, as a business, and in our world. This means acting in a safe, ethical manner in everything we do" (p. 1). The social dimension of sustainability is met by developing policies for inclusion in the workplace. GKN Aerospace promotes a safe environment, respecting the rights and diversities of the workforce (GKN Aerospace 3, 2021). Regarding the economic dimension of sustainability, GKN Aerospace aims to create constant development for each stakeholder involved, from the workforce to suppliers and all business partners (GKN Aerospace 3, 2021). The purpose is to "win in business but do so fairly" (p. 1). From the environmental perspective of sustainability, GKN Aerospace aims to reduce the impact of the manufacturing processes, by optimizing the design of the products and reducing their weight (consequently reducing fuel consumption) (GKN Aerospace 3, 2021).

1.3 Research questions (RQs)

For a comprehensive understanding of the research area, three research questions (RQs) were addressed.

RQ1 - *What are the factors that control the assignment of a product to a machine? How is it determined that a machine is technically capable of performing a certain operation?*

RQ2 - *How should the most appropriate machines (with respect to optimized resource allocation) be selected to perform a certain operation on a given product?*

RQ3 - *What additional technical information needs to be evaluated to carry out the allocations?*

1.4 Purpose

The primary purpose of the project is to examine both the given products and machines for identifying the critical parameters that have a direct effect on resource allocation. Resource allocation means developing structured and strategic plans to optimize the use of available resources (machines, workforce, etc.) to achieve balanced load levels in the factory (Fotedar et al., in press). After identifying the critical characteristics of both products and machines, the study proceeds analyzing the relationship between these two dimensions to develop effective resource allocation strategies. The main result includes matrices that represent the association between product features and machine capabilities that are specific to each operation. This result will assist GKN Aerospace to immediately compare both dimensions (product features and machine capabilities) and facilitate resource allocation decisions. Cutting operations represent the main contributor to GKN Aerospace's lead time, and, for this reason, they are the machining operations of main interest for this project (Fotedar et al., 2020).

With this framework, identifying the best resource allocation when it comes to changes or introduction of new products in production becomes straight and immediate. By adding additional factors (relating to quality, tolerances, time, costs, etc.) to the model, the assessment of resource allocation is further enriched with additional levels of detail.

1.5 Objectives

Two different objectives were framed, i.e., business and project objectives. The business objective aims to describe the middle- and long-term results that the project intends to deliver and often corresponds to the desired expectations of the company. It was identified by analyzing the stakeholders involved and their expectations for the project. The project objective aims to describe short-term results that the project intends to create and deliver.

1.5.1 Business objective

Facilitate GKN Aerospace's production system to be more flexible through effective resource allocation, in order to promptly and effectively handle changes in production, e.g., the introduction of new products into the factory.

1.5.2 Project objective

Deliver GKN Aerospace a method that can be used for establishing the relationship between product features and machine capabilities for a given set of machining operations.

1.6 Delimitations

The boundaries of this project are twofold, concerning both machines and products. On the machine's side, although for a complete and reliable picture it would be necessary to evaluate all the machines available in the factory, this could not be pursued due to time constraints. Hence, only machines capable of performing a few cutting operations, namely turning, milling and drilling, were evaluated. Machining processes other than cutting operations, e.g., welding, heat treatment, etc., are excluded. On the product's side, a similar limitation was placed, i.e., only three products that GKN Aerospace currently manufactures were evaluated to identify the product features on which to base the study. Furthermore, due to the unavailability of data, the functioning of the approach was tested only on two out of three products.

Other limitations concerned some technical aspects. The project does not include any mathematical optimization model or algorithm for the tactical allocation of machines to specific products. Only the study's approach and its operating mechanism are presented. No software was developed to automate the functioning of the approach. No plan to standardize the process used to carry out the approach was developed.

1.7 Thesis outline

An outline of the thesis is provided to guide the reader through this report. After the "Introduction" chapter, where the background of the study is described, the literature study is presented. The report continues with a brief description of the basic functioning of the jet engine, to facilitate the reader understanding of subsequent results. Thereafter, an explanation of the methods used is provided. The last part of the report concerns the results and their discussion, followed by a short conclusion, which summarizes the most relevant parts of the study.

2

Literature review

This chapter presents the literature study, aimed at expanding the background knowledge on the research area

2.1 Production systems

Suh et al. (1998) define a production system as “the arrangement and operation of elements (machines, tools, material, people and information) to produce a value-added physical, informational or service product whose success and cost is characterized by the measurable parameters of the system design” (p. 628). Production systems are structured configurations that deliver products or services, complying with defined standards and within certain limits (Najid et al., 2020). In the manufacturing environment, production systems are a set of resources (humans, machines, tools, materials, information, etc.) deputy to transform raw materials into final products (Najid et al., 2020).

2.1.1 Changes in production

Nowadays, there is a rapid change in customer requirements and market demand. The products’ life cycle is getting shorter. As a consequence, to counter this trend, the life span of production systems is required to last longer, in order to use the same production system for many product generations (AlGeddawy & ElMaraghy, 2010). Therefore, in order to accommodate fast changes in production, production systems and their capabilities are required to be more flexible and adaptable (ElMaraghy et al., 2005). The adaptability of production systems should be maximized to make sure that the existing capabilities can be fully utilized by satisfying the requirements for new products, before implementing new resources into the production system (AlGeddawy & ElMaraghy, 2010). Product designers are also under pressure to maximize the usage of existing machines before new capabilities are introduced into the production system (AlGeddawy & ElMaraghy, 2010). During the last few decades, the manufacturing sector is experiencing a rapid introduction of new materials and technologies (ElMaraghy et al., 2012). As a consequence, as ElMaraghy et al. (2012) state, “there is a clear need for innovative product design and manufacturing approaches to ensure competitiveness, responsiveness, and sustainability” (p. 2).

There are two basic ways to handle product variations and changes in production: physical and logical change management (AlGeddawy & ElMaraghy, 2010). Physical adaptation concerns the physical relocation, resetting, reconfiguration, addition/removal or replacement of manufacturing resources within the production system (AlGeddawy & ElMaraghy, 2010; ElMaraghy et al., 2005). This leads to high environmental and economic impact and increases the production system's complexity (ElMaraghy et al., 2005). Logical adaptation, on the other hand, helps to handle product changes by reconfiguring, rerouting, rescheduling, replanning, reprogramming and classifying products into product categories (or product families) within which they share the same technical features (ElMaraghy, 2005; AlGeddawy & ElMaraghy, 2010). Logical change management, therefore, does not involve physical changes within the production system, thus avoiding the negative consequences that characterize physical adaptation. However, both physical and logical change management adapt production systems from a unilateral perspective, i.e., the product (AlGeddawy & ElMaraghy, 2010). Hence, to obtain effective adaptation, a bilateral perspective needs to be implemented. Therefore, not only product features must be evaluated, but they need to be combined with the analysis of manufacturing resource capabilities (AlGeddawy & ElMaraghy, 2010). This will be further investigated in Section 2.3.

2.1.2 Production system evolution

To stay competitive in today's unpredictable and rapidly changing market, companies need to adapt their production systems to react to this volatility (Najid et al., 2020). This has always been the case since the first industrial revolution started in the 18th century, when the switch from craft to mass production took place. Retracing history, production systems have continued to change, right up to mass customization, ending with personalized production (Najid et al., 2020). Figure 2.1 shows this evolution by assessing two parameters, the ones that are more affected by the shifts between production systems, i.e., product variety (on the x-axis) and product volume per product variant (on the y-axis) (Najid et al., 2020).

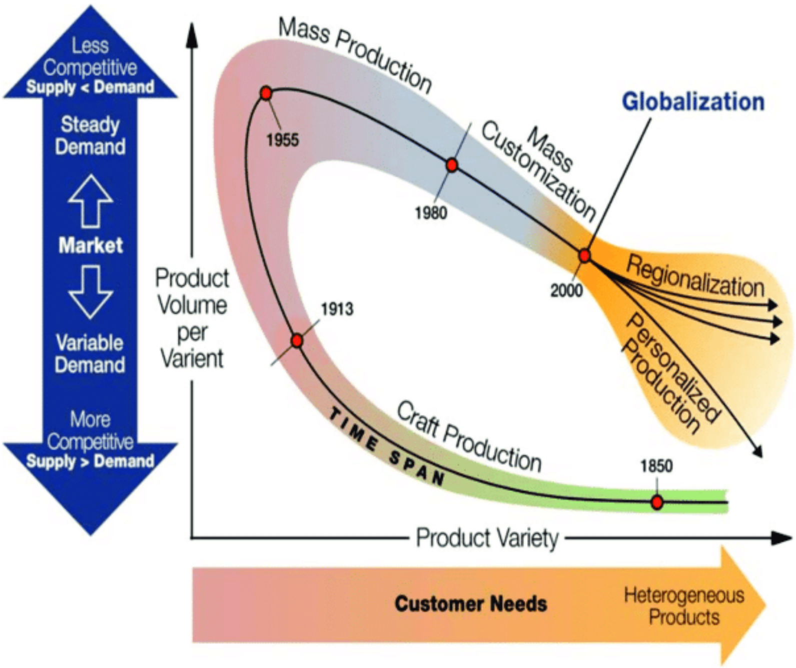


Figure 2.1: The evolution of production systems (Najid et al., 2020)

2.1.3 Production system complexity

The production system's complexity is one of the causes of its ineffectiveness to manage changes (Kim, 1999). A production system may manufacture hundreds of products, made of several part types, and may consist of equally numerous machines, which might fail when it is least expected (Kim, 1999). Due to the requirements for new production systems to be flexible and adaptable to effectively handle changes in production, they are required to process a larger amount of information than before, thus significantly increasing their structural and operational complexity (Kuzgunkaya & ElMaraghy, 2006). Kuzgunkaya and ElMaraghy (2006) propose a metric to classify the complexity of production systems. The model aims at selecting the production system categorized as less complex, but which still strictly comply with the requirements. As the number of machines and the products to be manufactured increases, the complexity of such manufacturing systems increases accordingly (Kuzgunkaya & ElMaraghy, 2006). The complexity is mainly due to the high number of allocation options, determined by several associations between machines and product features. This huge number of associations leads to a large amount of information to analyze, hence increasing exponentially the system's complexity (Kuzgunkaya & ElMaraghy, 2006). Complex production systems allow handling and processing of large and varied amounts of information compared to limited and fixed production systems (ElMaraghy et al., 2005). However, if on one hand complex production systems help to quickly and effectively predict their behaviour when unexpected changes occur or new products are introduced in production, on the other hand, this whole complex amount of information is difficult to interpret (ElMaraghy et al., 2005). Therefore, to make a production system work, complexity must be measured, categorized and treated with approaches aimed at managing it (Kim, 1999).

In this regard, ElMaraghy et al. (2005) suggest the use of a mathematical model to synthesize this information and ensure smoother management of complexity.

ElMaraghy et al. (2005) state that manufacturing complexity is made of three elements that need to be analyzed:

- The product complexity takes into consideration the product features.
- The process complexity focuses on the manufacturing operations.
- The operational complexity analyzes the combination of the product and manufacturing process.

The analysis of these three elements allows for obtaining a comprehensive understanding of the production system's complexity. However, it's important to notice that, although complex manufacturing systems allow adaptability and flexibility, they are expensive solutions (ElMaraghy et al., 2005). The impact of complexity on costs should not be underestimated when implementing, running, and maintaining such production systems (ElMaraghy et al., 2005).

2.1.4 Flexibility and reconfigurability in production

Reconfigurable Manufacturing System (RMS) and Flexible Manufacturing System (FMS) are solutions to quickly respond to changes in production and make the production system flexible and adaptable (ElMaraghy, 2005). ElMaraghy (2005) compares the two systems, highlighting their different approaches to flexibility.

2.1.4.1 Reconfigurable Manufacturing System (RMS)

Kuzgunkaya and ElMaraghy (2006) suggest implementing RMS to meet the continuously changing requirements of new production systems. The main aspect of the RMS would be to reduce the lead time when introducing new products, and also increase the reconfiguration speed of the existing system (ElMaraghy, 2005). RMS automatically adapts to the production environment by redesigning its hardware and software capabilities according to the changing requirements (Kuzgunkaya & ElMaraghy, 2006). These systems use concepts such as modularity and scalability to achieve a satisfactory degree of flexibility in the production system (Koren, 2020). RMS allows customizable and variable flexibility for unknown production variations in a significantly shorter time frame than FMS, without keeping the production system's capacity and capabilities fixed (ElMaraghy, 2005). It represents a cost-effective means to forecast and meet future demand in the current volatile global market (Koren, 2020). Reconfiguration alternatives are limitless, therefore a model that ensures the selection of the least complex and expensive solution is needed (Kuzgunkaya & ElMaraghy, 2006). This is also the reason why a mathematical model to synthesize this information is recommended (ElMaraghy et al., 2005). The key characteristics for a RMS are summarized in Table 2.1 (Mehrabi et al., 2000).

Table 2.1: RMS's key characteristics (Mehrabi et al., 2000)

Key characteristic	Detail
Modularity	The production system and its components are designed to be modular.
Integrability	The production system and its components are designed to be easily integrated when changes in technology occur.
Convertibility	The production system and its components are designed to be easily adapted when changes in production occur.
Diagnosability	The production system and its components are designed to be reactive to quality problems that may occur.
Customization	The production system and its components are designed to be flexible in meeting different customer's requirements.

2.1.4.2 Flexible Manufacturing System (FMS)

One of the reasons for the inception of the FMS was due to the demand for small lot sizes of several products (AlGeddawy & ElMaraghy, 2010). The main difference with RMS is the type of flexibility that can be achieved. First of all, FMS does not allow a customizable flexibility. Therefore, the achievable flexibility is somehow general, not specifically designed for the given production system. Secondly, FMS does not allow flexibility for unknown products. Only well-known products can benefit from this type of flexibility (ElMaraghy, 2005). The cost is another major difference between the two systems. In order to be able to handle the production of a variety of products at the same time, FMS requires a high capital investment. (ElMaraghy, 2005).

2.1.5 Measuring flexibility

Without a doubt, in today's evolving manufacturing environment, flexibility is an essential requirement. However, flexibility is an elusive concept, difficult to precisely define and categorize (Fotsoh et al., 2020). Rogalski and Wicaksono (2012) demonstrate that there are no methods in place to categorize and estimate flexibility in production systems. As a consequence, it is not easy to understand whether a production system lacks flexibility or not and assess the required degree of flexibility that a production system should have (Rogalski & Wicaksono, 2012). The ecoFLEX methodology allows for a global evaluation of flexibility, by evaluating the production system on multiple levels and differentiating between different industrial sectors. The ecoFLEX method can be used through software, which helps identify the current weaknesses related to the flexibility of the production system, categorize and then reduce them (Rogalski & Wicaksono, 2012).

2.2 Key Characteristics (KCs)

Identifying and keeping track of all product and machine characteristics is an unrealizable effort (Dantan et al., 2008). From the product side, controlling thousands of features is not materially feasible; for the machines, it is a useless effort trying to control all the processes. Only the product features and machine capabilities that directly affect the overall results to a greater extent, whose variation generates significant problems (decreased quality, performance, safety and increased costs), must be taken into consideration. These critical characteristics are defined as Key Characteristics (KCs) and are presented for both the products and machines in the next section (Dantan et al., 2008).

Nowadays, the adoption of new production processes and technologies has exponentially expanded the manufacturing approaches of the aerospace industry. As a consequence, a standardized and methodical procedure, aimed at evaluating each possible manufacturing approach (and the resulting variations), must be put in place. Basing the evaluation of the outcome of each of these approaches on KCs is an effective way to make this process systematic and reliable (Madrid et al., 2016).

2.2.1 Key Product Features (KPFs)

In today's highly competitive market, the three main pillars that companies are demanded to base their production on are low costs, high quality and short lead times. To pursue this, Key Product Features (KPFs) need to be identified and selected (Tang et al., 2014). KPFs represent a set of product/part characteristics whose variation leads to severe consequences on the product's function, quality and cost (Dantan et al., 2008). Features can have different meanings in different contexts. In the design context, feature can be e.g., a notch section; in manufacturing, it can be e.g., a hole or plane; during the inspection, it can be e.g., a reference point for inspection (Peng et al., 2017). Tang et al. (2014) argue that the process of identifying KPFs is much more difficult for complex sectors, such as aerospace, due to the usual product complexity and large varieties. The identification and selection of KPFs ensure high-quality standards for the final product (making it possible to carefully analyze quality indexes, e.g., tolerances, geometry, failure rates, etc.) and allow an optimized use of the manufacturing resources (Tang et al., 2014). In order to make the identification of KPFs reliable, Tang et al. (2014) propose a top-down approach to decompose them. This model presupposes that KPFs have different importance; indeed, they can be divided into levels according to their impact on the final result. Top-level KPFs are the top of the hierarchical three of KPFs and concern essential features, such as customer requirements and manufacturing requirements. Starting from the top-level KPFs, the three is decomposed in several sub-levels, until it reaches levels that cannot be divided further (Tang et al., 2014).

Product categorization into family products is the way to proceed to ensure the mapping of the common KPFs and then allocate the right resource. The identification of a common product value stream is a good starting point. Products that are part of the same value stream share similar design and technical features (Fotedar et al., 2019). This also has a practical twist when it comes to quality controls (e.g., tolerances, failure rate, scrap rate, etc.) on machines manufacturing similar products. Quality controls represent an important prerequisite in the aerospace sector since any type of non-conformance leads the production to stop (Fotedar et al., 2019). This also allows studying the feasibility of the allocation of a new product to an existing machine. After identifying the value stream, a list of machining operations is prepared (Fotedar et al., 2019).

2.2.1.1 Product families

Products are complex and made of several different parts, with different specifications, designs and functionalities (Whitney, 2006). A method to systematize them is thus required. In some market segments, such as the aerospace sector, the large product diversity might cause problems when it comes to efficiently and cost-effectively handling manufacturing processes (Agard & Kusiak, 2004). The ability to properly group products into families is crucial to adequately and smoothly manage the production system (Abdi & Labib, 2004). In such a scenario, Agard and Kusiak (2004) propose to introduce a certain degree of standardization in the production system by dividing products into product families. This approach ensures production processes to easily manage manufacturing diversity, with the advantage of lowering costs. Ham et al. (1985) define product family as a group of products that presents analogies from design, technology and manufacturing processes perspectives. Agard and Kusiak (2004) describe a three-step methodology to design a product family (Figure 2.2). The first step aims at identifying customer requirements. A detailed analysis of the functional requirements that the product is expected to deliver, according to the customers' point of view, is carried out. The second step, based on the analysis of the customer requirements performed at the first step, aims at designing the functional structure for the product family. The last step aims at developing the technical structure allowing the production of the products belonging to the product family identified (Agard & Kusiak, 2004).

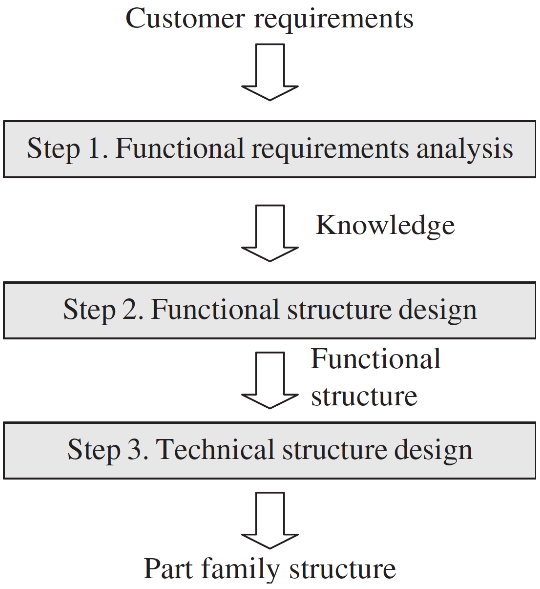


Figure 2.2: The three-steps methodology to design a product family (Agard & Kusiak, 2004)

2.2.1.1.1 RMS and product families A requirement to make sure a RMS works effectively is that products are categorized into families, to ensure the allocation of the right manufacturing resources (Abdi & Labib, 2004). Xiao-bo et al. (2000) demonstrate the close link between RMS and product families, i.e., each product family represents a specific configuration of the RMS. In addition, RMS allows for accommodating the introduction of new products into product families, within certain limits (Abdi & Labib, 2004). Overall, grouping products into families is a prerequisite that allows RMS to successfully handle product variants, as products are categorized according to their features and manufacturing requirements (Abdi & Labib, 2004). There are several rules on which to base the categorization of products into families, e.g., based on design, functional requirements, technology, machines, materials, process similarities, etc. (Abdi & Labib, 2004).

2.2.1.1.2 Datum Flow Chain (DFC) The Datum Flow Chain (DFC) is a diagram intended to illustrate the relationship between the parts that make up a product. This process ensures that all the parts are assembled in the right place, with the right dimensional tolerance (Whitney, 2006). Whitney (2006) states that “the DFC serves first to locate the key parts with respect to each other” (p. 4). As a consequence, the DFC translates into a quality requirement for the final product. However, before building a DFC, it is suggested to build a KPF flow-down diagram, showing a breakdown of all the parts that make up the final product and their hierarchical assembly order (Whitney, 2006).

2.2.1.2 Categorization of product features

There are many approaches in the literature to categorize product features. The most adopted is the one created by AlGeddawy and ElMaraghy (2011) and embraced by Kou and Xi (2018), which propose a categorization of KPF into six groups, containing 12 parameters in total. They are listed in Table 2.2.

Table 2.2: Product features according to AlGeddawy and ElMaraghy (2011)

Part feature	**Feature state**
Dimensionality	Rail Cube
Shape	Rectangular cross section Nonrectangular Compound block
Rotational features	Do not exist Exist
Machined surfaces	One direction Stepped surfaces from one direction More directions
Special surfaces	No features Keyways or grooves Complex surfaces
Auxiliary holes	Do not exist Exist

2.2.1.3 Standardization of product features

One of the biggest limitations to the quick and cost-effective design of parts/products and to the management of their variation, is the lack of standardization (Landahl et al., 2020). The standardization of, and then the capability of quickly and economically reuse, physical components and intangible design elements (i.e., functions and technologies) is the way to solve this problem (Landahl et al., 2020). Landahl et al. (2020) define it as a product platform and state that it "is supported by the aim of product family design, modularization and the decomposition of product architecture" (p. 4). Meyer and Lehnerd (1997) define a product platform as "a set of common components, modules, or parts from which a stream of derivative products can be efficiently created and launched" (p.7). However, if on one hand product platforms represent an economic solution to reuse physical parts and components, on the other hand they offer low flexibility when changes in production occur (Landahl et al., 2020). Therefore, Landahl et al. (2020) propose to look at the problem from another perspective, i.e., combining product and production platforms to be able to find optimized solutions when variations in production occur. The integration of both product and production platforms is defined by Landahl (2018) as co-platforming. Co-platforming helps the connection of design and production, required to handle variations and changes in production (Landahl, 2018).

Another limitation to the establishment of a standardized and integrated production system is the lack of standardized information (Al-wswasi & Ivanov, 2019). When it comes to product data, it is pretty common in production that each department adopts its own standard (Al-wswasi & Ivanov, 2019). Part features identified with a Computer-Aided Design (CAD) software, showing the geometrical and dimensional features of the product, are incompatible with the data identified with a Computer-Aided Process Planning (CAPP) software, showing the manufacturing characteristics; they are also both incompatible with Computer-Aided Manufacturing (CAM) data (Al-wswasi & Ivanov, 2019). As a consequence, their integration is difficult, simply because they use different standards to categorize data. This, of course, severely hampers the information flowing smoothly within the factory, thus affecting the quick launch of products into the market (Al-wswasi & Ivanov, 2019).

2.2.1.3.1 Automatic Feature Recognition (AFR) As described in the previous section, the main problem in production standardization lies in the difficult integration of product design, which is based on the assessment of geometrical and topological data (relationships of the features (Albert, 2001)), and process planning, which is based on the assessment of manufacturing resources (Al-wswasi & Ivanov, 2019). The conversion from product design information into manufacturing information is a complex, time-consuming and expensive operation (Al-wswasi & Ivanov, 2019). In the current industrial environment, there is a need for tools that can automatically identify product features. Fortunately, there is a strong technological effort aiming at easing the integration of these two production dimensions (Albert, 2001). Al-wswasi and Ivanov (2019) propose an Automatic Feature Recognition (AFR) approach, aimed at bridging the gap between the data from these three product dimensions and implement a shared standard between CAD, ACAPP (which is an updated version of CAPP) and CAM. The AFR approach derives the basic geometric information from the CAD model, e.g., holes, slots, pockets, bosses, fillets, etc.; it then converts it into manufacturing features for the CAPP, which finally converts this information for the CAM software (Al-wswasi & Ivanov, 2019). AFR, and the further allocation of corresponding machining operations and routes stored in a database, leads to higher productivity and reduction of bottlenecks in the production flow. The database consists of all machining parameters, e.g., speed, angle, feed, tool, type of material to be machined and optimal machining routes (Albert, 2001). Albert (2001) also demonstrates another beneficial effect of the automation of feature recognition, i.e., cost estimations can be automated too, and they can become quicker and more precise. The same is true from the customer perspective, i.e., price quotations can be automated, and they can become quicker and more precise too (Albert, 2001).

2.2.1.3.2 STandard for the Exchange of Product data (STEP) All shareholders involved in a specific product realization need to continuously exchange and share their data and information (Lipman & Lubell, 2015). Different departments within the same company use different software (with different proprietary formats) to process data. This hampers a smooth information exchange and requires continuous data translations, which is expensive in terms of time and costs (Hunten et al., 2013). Lipman and Lubell (2015) claim that “data exchange standards define an agreed-upon syntax and structure of 3D modelling constructs and annotations for tolerances and dimensions so that all participants in the manufacturing supply chain can understand each other’s models” (p. 14). The STandard for the Exchange of Product data (STEP) is an international standard (ISO 10303) that allows data compatibility through the whole manufacturing system and during the entire product life cycle, ensuring a standard representation for dimensional information and tolerances (Feeney et al., 2015). Albert (2001) define STEP as “the grand international effort to alleviate the obstacles to the exchange of data” (p. 1). STEP is based on a set of data defined as Product and Manufacturing Information (PMI), which covers both geometric features and manufacturing dimensions (Lipman & Lubell, 2015). STEP makes the interaction of these two production dimensions possible, by creating neutral files readable by all software (Albert, 2001). The machining operations (including specific working steps and routes) performable on Computerized Numerical Control (CNC) machines are specified by an extension of the STEP standard, called STEP NC (Albert, 2001). This is, in practice, how the link between the two production dimensions takes place. For example, the company OPEN MIND Technologies AG developed the hyperMILL CAM system, which aims to accelerate Numerical Control (NC) programming. hyperMILL allows the selection of the design features that are crucial for the machining operations on the product. These features are automatically identified by the system and the associated machining information is automatically generated (OPEN MIND Technologies AG, 2021). STEP files are convenient because they contain both geometrical data, such as “vertices, edges, curves, surfaces, and relations” (Al-wswasi & Ivanov, 2019, p. 262), and non-geometrical data, such as “materials, view, general note, witness line, leader, and associativity entities” (Al-wswasi & Ivanov, 2019, p. 262). Hunten et al. (2013) describe the “protection against the obsolescence of proprietary formats” (p. 1215) as another advantage of using an open standard as STEP. The main limitation of using a STEP for an AFR approach is the limited ability to identify new features, for instance when new products are introduced into the factory (Al-wswasi & Ivanov, 2019).

2.2.1.3.3 Quality Information Framework (QIF) Quality Information Framework (QIF) is another CAD standard that allows, as STEP does, the interaction between product design and machining information (QIF Standards, 2021). The QIF was developed by the Digital Metrology Standards Consortium (DMSC), it was approved by the International Organization for Standardization (ISO) in August 2020 and published as ISO Standard ISO 23952:2020 (QIF Standards, 2021). QIF is also approved by the American National Standards Institute (ANSI) (QIF Standards, 2021). DMSC (2018) defines QIF as “an integrated set of information models which enable the effective exchange of metrology data throughout the entire manufacturing quality measurement process – from product design to inspection planning to execution to analysis and reporting" (p. xxv). DMSC (2018) explains that the QIF measurement process consists of five steps:

1. Definition of the product
2. Identification of measurement requirements
3. Definition of the measurement process
4. Execution of the measurement process
5. Analysis of the measured data

2.2.1.3.4 Smart Interactive Automatic Feature Recognition (SI-AFR)

To overcome the limitations of using STEP files, Al-wswasi and Ivanov (2019) propose an upgrade of the AFR approach, the smart interactive AFR (SI-AFR). The SI-AFR is made of two parts:

- Recognition of predefined features - This section aims at identifying the existing part features and saving in a database all the data retrieved.
- Interactive feature recognition - This section can be activated when new products/parts are introduced into the production system. As a result, the new part features are identified and the data is stored in the same database as for the previous section. In this way, new part/product features are added to the predefined feature set identified through the "recognition of predicted features" section (Al-wswasi & Ivanov, 2019).

Due to the capability of SI-AFR to recognize already existing and new part/product features, the approach is considered to be reliable and complete. However, even if the SI-AFR system can overcome the main issue of AFR systems (not considering new part/product features), it still presents the problem of not being able to recognize all the geometrical features, e.g., freeform surfaces cannot be identified (Al-wswasi & Ivanov, 2019).

2.2.2 Key Machine Capabilities (KMCs)

The right selection of machining parameters is a crucial choice in all machining operations in the industry. It makes it possible to fully exploit the equipment utilization and reduce all types of wastes, from scrap rate to machining costs (Peng et al., 2015). This is the reason why machine capabilities need to be identified and categorized. Dantan et al. (2008) define Key Machine Capabilities (KMCs) as the machine characteristics, parameters, fixtures and equipment which substantially influence the final result on the products to be machined. Gologlu (2004) looks at machine capabilities from a different perspective. He identifies machine capabilities (including their geometries, dimensions, tolerances and fixturing systems) as constraints of manufacturing operations. Deleryd (1996), instead, defines capability as "the ability of a process to produce products according to specified requirements" (p.6). Of course, this definition embraces a wide set of concepts, depending on the context. In the case of machine capability, it refers to the ability to machine most of the products within specified tolerances (Larsson, 2002). In detail, Larsson (2002) defines machine capability as the ability to manufacture a specific product feature "with no effect from the environment and changes in time, e.g., temperature changes and tool wear" (p. 25).

2.2.2.1 Categorization of machine capabilities

AlGeddawy and ElMaraghy (2011) propose a categorization, then adopted by Kou and Xi (2018), of KMCs into six groups, containing 11 parameters in total. They are listed in Table 2.3.

Table 2.3: Machine capabilities according to AlGeddawy and ElMaraghy (2011)

Machine capability	**Capability state**
Structure	Horizontal Vertical
Axes of motion	3 axes 4 axes 5 axes
No. of machining heads	One Two
Turning spindle	No turning spindle Turning spindle
Turret/Tool magazine	None Exists
Control	Manual CNC

In 2001, the ISO proposed the standard for "mechanical product definition for process planning using machining features", aimed at defining a standard for machining characteristics (Peng et al., 2015). This is, however, a more general classification that takes into consideration different information, not all directly related to machine capabilities, but that indirectly affect them (Peng et al., 2015). According to this approach, the machining features comprise five groups:

- Part feature
- Geometric information
- Material information
- Precision information
- Manufacturing resources information

The structure of this approach is shown in detail in Figure 2.3.

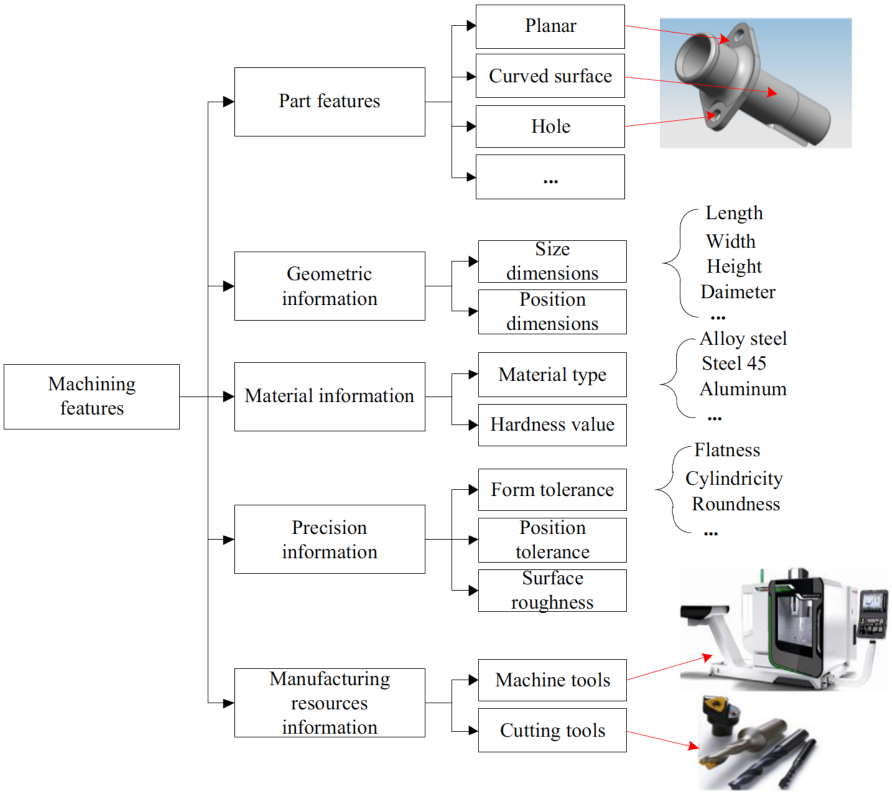


Figure 2.3: The structure of machining features (Peng et al., 2015)

2.2.2.2 Optimal sequencing of machining operations

Categorizing machines according to their KMCs is not enough. In order to obtain smooth and effective machining processes, machining operations (and sub-operations) sequencing is a crucial activity that must be strategically planned. The optimal sequencing of machining operations aims at reducing changeover and lead time, hence making the production system handle a variety of products in a lean and optimized way (Azab & Gomaa, 2012). An optimization process, aimed at sequencing machining operations, just based on pre-defined product families, does not meet the requirements for a continuously evolving production system (Azab & Gomaa, 2012). Azab and Gomaa (2012) propose a mathematical model which, based on advanced algorithms that automatically adapts to changes in the manufacturing environment, creates an optimal operations sequencing. The result is the minimization of the time lost between two subsequent machining operations (or sub-operations), thus reducing wasted time (Azab & Gomaa, 2012).

2.2.2.3 Relationship between machine capabilities and RMS

There is a close relationship between RMS and the use of KMCs (Asghar et al., 2018). Asghar et al. (2018) claim that defining KMCs during the product design stage and reusing them during the reconfiguration phase (e.g., in case of production changeovers) lead to reduction of costs and increase in productivity. The aim of the

Asghar et al. (2018) research is to evaluate the occasions when the reconfiguration of the production system is actually required and how to accomplish reconfigurability with the minimum amount of machine capabilities. The method used to do so is somehow complex and requires mathematical algorithms to obtain optimum machine capabilities. Apart from the complexity issue, this method helps the reconfiguration of production systems in the case of market uncertainties, performing production operations with optimized machine capabilities (Asghar et al., 2018).

2.3 Relationship between product features and machine capabilities

Nowadays, with the ever-changing market and its vulnerability, both products and production systems face frequent changes and variations (Kashkoush & ElMaraghy, 2017). Product life cycles are becoming shorter and shorter, as are the life cycles of production systems (AlGeddawy & ElMaraghy, 2012). To counteract this tendency, it is becoming more and more important to quickly and economically adapt machine capabilities to the request for new product features. It is, therefore, crucial to gain knowledge about current or old products on one side, and about the corresponding production system and its capabilities on the other side. In this way, correlations between new products introduced in production and the current production system can be easily found. The result is fast adaptability of the production system and its capabilities to the new product specifications (Kashkoush & ElMaraghy, 2017).

In Section 2.1, the limitation of handling changes in production from just the product perspective was examined. It was stated that, in order to effectively manage adaptation, a bilateral perspective, both from the product and manufacturing resources, should be implemented (AlGeddawy & ElMaraghy, 2010). It is therefore clear that, due to last decades' manufacturing challenges, a joint design and development of products and manufacturing resources need to be implemented (Michaelis & Johannesson, 2012). Kou and Xi (2018) state that “a strong association exists between the design of products and the machine capabilities of their manufacturing” (p. 1).

2.3.1 Models found in literature

Many models aimed to combine product features and manufacturing resource capabilities can be found in literature. Some of them are presented in the following sections.

2.3.1.1 Manufacturing co-evolution model from AlGeddawy and ElMaraghy (2010)

The manufacturing co-evolution model derives from cladistics, a typical method of biology that categorizes animal or plant species according to measurable characteristics that they have in common (Baldwin et al., 2012; AlGeddawy & ElMaraghy, 2010). By translating this model to manufacturing environments, it demonstrates that, in a production system, the product features and machines capabilities cannot be disjoined from each other (AlGeddawy & ElMaraghy, 2010). This is what actually co-evolution means in biology, i.e., when two or more different species affect the evolution processes of each other (AlGeddawy & ElMaraghy, 2012). AlGeddawy and ElMaraghy's (2010) study shows that "a product change leads to a reactive change in the manufacturing capabilities and vice versa, where the magnitude of the change reaction is proportional to that of the original change" (p. 2). The comparison between product features and machine capabilities is done using cladistics. The similarities found thanks to this categorization are of interest for the co-evolution model (AlGeddawy & ElMaraghy, 2010). The model is based on cladograms, diagrams showing cladistic relationships between species (Baldwin et al., 2012). Cladograms are generated for both product features and machine capabilities. The manufacturing co-evolution model, then, finds the best match between the two sides cladograms (so called "tree reconciliation technique"), as shown in Figure 2.4 (AlGeddawy & ElMaraghy, 2010). Kashkoush and ElMaraghy (2017) demonstrate that "corresponding branches of systems and products trees provide relationships between manufacturing capabilities and product features" (p. 1033).

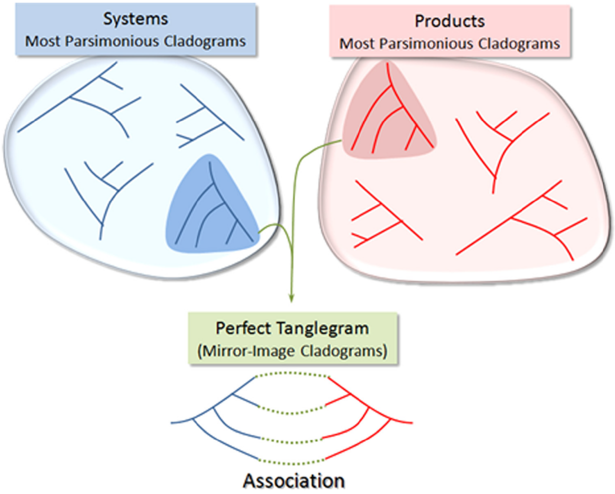


Figure 2.4: Trees reconciliation and cladograms comparison (AlGeddawy & ElMaraghy, 2012)

When well established and properly developed, the manufacturing co-evolution model is capable to predict the future behaviour of the production systems in relation to new products, which can be manufactured with the available machine capabilities (AlGeddawy & ElMaraghy, 2012).

2.3.1.2 Tactical resource allocation model from Fotedar et al. (2019)

Fotedar et al. (2019) present a model, the tactical resource planning, aimed at helping to reduce imbalances and uncertainties in production systems. It is also meant to help track the routing of products within the production system and provide guidance to select optimal machines (Fotedar et al., in press). The model makes the production system quickly adaptable to changes in production and reduces capacity imbalances. The study by Fotedar et al. (in press) shows the issues encountered at GKN Aerospace when it comes to balancing the machine's capacity level. The tactical resource allocation model aims at solving these problems and finding new routes (rerouting flexibility) to avoid that only certain machines are loaded, thus becoming bottlenecks (Fotedar et al., in press). The reason for these capacity issues at GKN Aerospace is that machines are all shared and capable of multiple machining operations. As a result, feasible allocations are numerous and complex (Fotedar et al., in press). This is why Fotedar et al. (in press) propose to solve the problem with the support of mathematical optimization algorithms.

There is a crucial difference between tactical resource allocation and short-term resource allocation. They are both part of the logical adaptation described by AlGeddawy and ElMaraghy (2010), but they operate on a different time frame. Short-term resource allocation generally takes place in conjunction with scheduling and production planning operations, while tactical resource allocation takes place during the development phase of the production process. When the development phase of the production process is completed, the tactical resource allocation takes over (Fotedar et al., 2019). The tactical resource allocation model aims to effectively allocate products to resources, mainly when there are changes or the introduction of new products into the existing production system is crucial (Fotedar et al., 2019).

The main drawback of the tactical resource allocation model, which in many cases prevents its use, is its computational complexity. The model ends up with a too large number of solutions that needs to be analyzed to find the most suitable one (Fotedar et al., 2019). Fotedar et al. (2019) propose to solve this issue by using a mathematical optimization theory, helping to reduce the number of suitable solutions, evaluate them and find the optimal solution in a reasonable time frame. This mathematical model is discussed in more detail in Section 2.3.1.3.

2.3.1.3 Mathematical model from Fotedar et al. (2020)

When the manufacturing resource pool is very large, thus making it impossible to assess all machines, a mathematical model can be implemented to make sure to find the optimal allocation in a reasonable time frame (Fotedar et al., 2020). The mathematical model presented by Fotedar et al. (2020) focuses on capacity management, ensuring to have the right amount of capacity at the right time and at the right machine. The simplified model structure consists of two parts:

- Constraints represent the delimitations in which the optimal solution must lie.
- Objective functions are the target that the optimal solution should achieve

from the decision makers' perspective.

The mathematical model results in keeping the capacity load on machines within a specified range. This is possible by qualifying new machines to perform a given machining operation (Fotedar et al., 2020).

2.3.1.4 Platform-based co-development model from Michaelis and Johannesson (2012)

According to Michaelis and Johannesson (2012), products and production systems (hence manufacturing resources) need to be designed, developed and modified closely together until they are satisfactorily aligned to each other. The model presented by Michaelis and Johannesson (2012) is platform-based, meaning that a system aimed at designing and developing a structure to handle variations and changes is in place (Michaelis & Johannesson, 2012). Four main setups of the co-development model are possible:

- Dedicated co-development - No platform approaches are in place, neither for the development of the product nor for the development of the manufacturing system. Just one final solution, which matches one product solution with one manufacturing system solution, is feasible for this setup (Michaelis & Johannesson, 2012).

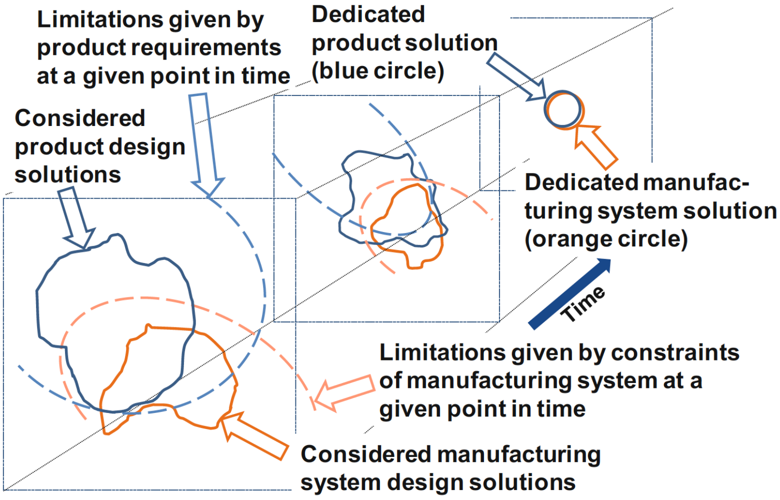


Figure 2.5: Dedicated co-development (Michaelis & Johannesson, 2012)

- Product-platform-based co-development - This setup presents a platform approach for product development. As a consequence, there is a range of optimal solutions that includes several products (within certain limits). On the other hand, the manufacturing system presents just one solution. Several final solutions, which match with the range of product solutions with the one manufacturing system solution, can be found (Michaelis & Johannesson, 2012).

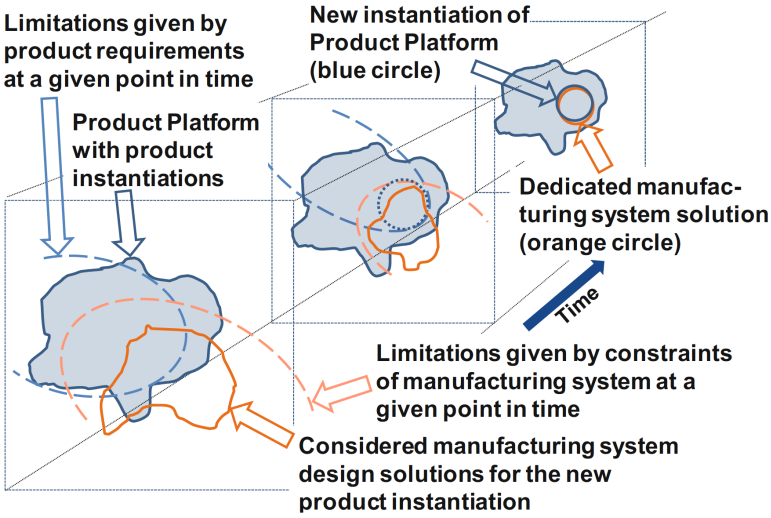


Figure 2.6: Product-platform-based co-development (Michaelis & Johannesson, 2012)

- Manufacturing-platform-based co-development - In this case, a platform approach for the manufacturing system development is in place, but not for the product development. This setup provides a range of optimal solutions that include several manufacturing systems (within certain limits). On the other hand, the product development presents just one solution. Several final solutions, which match the range of manufacturing systems solutions with the one product solution, can be found (Michaelis & Johannesson, 2012).

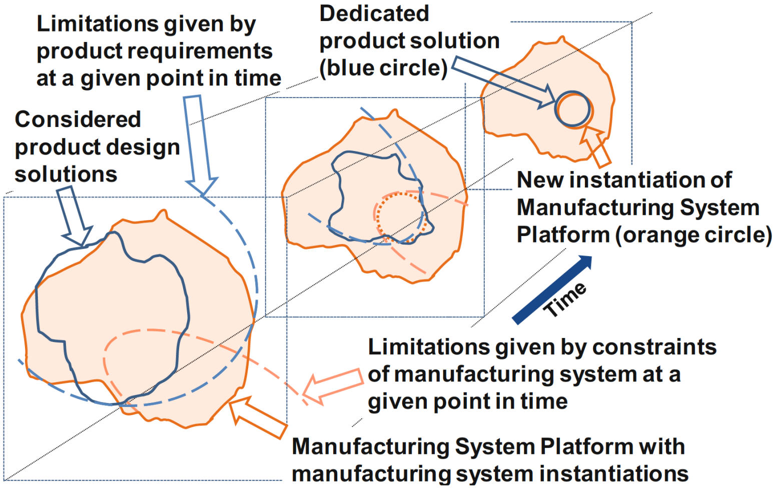


Figure 2.7: Manufacturing-platform-based co-development (Michaelis & Johannesson, 2012)

- Platform-based co-development - Two platform approaches exist, both for product and manufacturing system development. Several final solutions exist, thus allowing for multiple alignments between products and manufacturing systems (Michaelis & Johannesson, 2012).

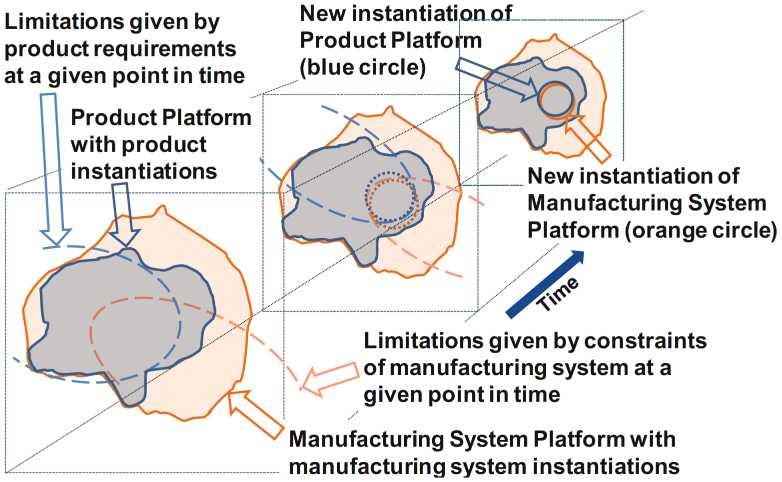


Figure 2.8: Platform-based co-development (Michaelis & Johannesson, 2012)

The four setups, of course, represent extreme cases for the co-development model. Within them, there is a range of possibilities to be explored (Michaelis & Johannesson, 2012).

2.3.1.5 Integer programming model from Kashkoush and ElMaraghy (2017)

This knowledge-based discovery model collects historical data and patterns concerning the associations between manufacturing system capabilities and product features and uses this information to design and develop the manufacturing capabilities when it comes to introducing new products (with new features) in the factory. This reduces manufacturing lead times and allows for faster product development and effective production system reconfiguration. To find correlations between product features and machine capabilities, the model uses an algorithm known as *association rule discovery* (Figure 2.9), which identifies associations between data collected from current or old products and machines. This data concerning correlations between machine capabilities and product features is eventually used to determine new associations in production (Kashkoush & ElMaraghy, 2017).

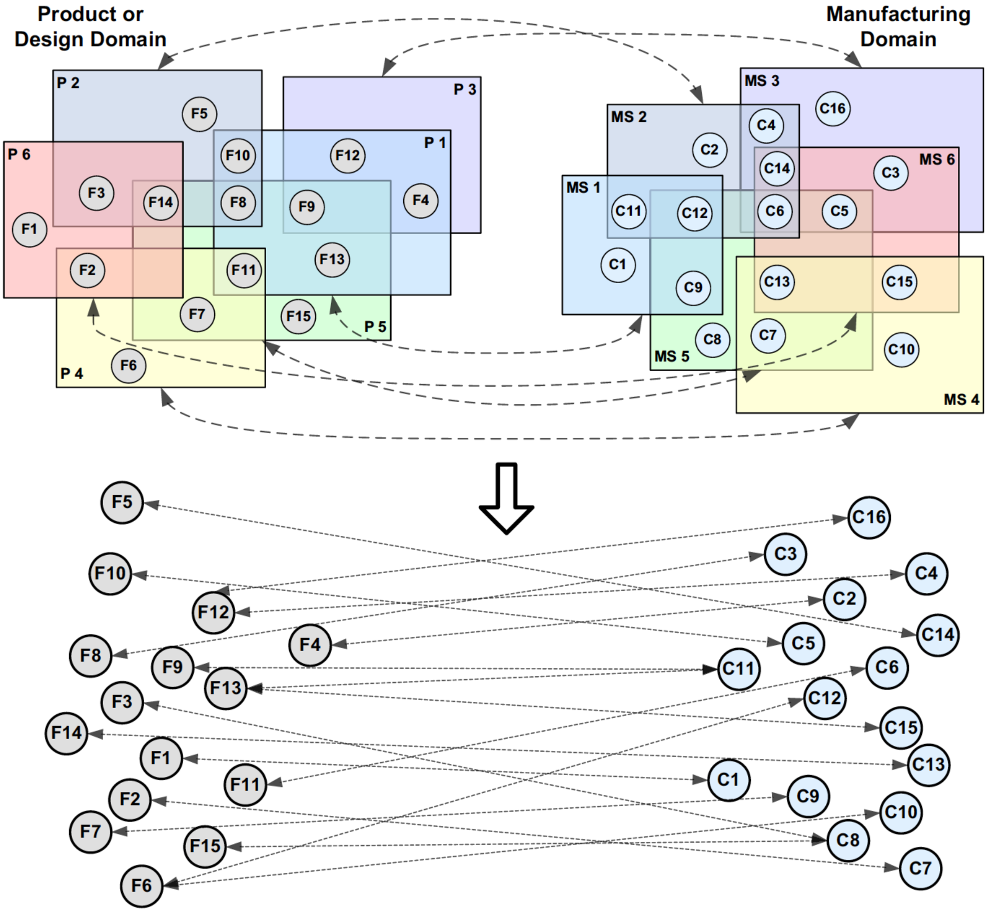


Figure 2.9: Association rule discovery problem (Kashkoush & ElMaraghy, 2017)

This model is complete because it employs constraints to ensure that the right correspondence between machine capabilities and product features is found and to avoid that machine capabilities that are mutually exclusive or redundant are related to each other with the same product feature (Kashkoush & ElMaraghy, 2017).

The Kashkoush and ElMaraghy' research (2017) applies the model to a case study, describing the steps involved. The first step is the categorization of the input data for both the manufacturing capabilities and product features. The case study concerns seven milling machines. Both manufacturing capabilities and product features data are categorized according to the AlGeddawy and ElMaraghy (2011) method. They are presented respectively in Figure 2.10 and Figure 2.11.

Machine	Manufacturing capabilities										
	1		2			3		4	5	6	
	Structure		Axes of motion			No. of heads		Turning spindle	Turret/tool magazine	Control	
	Vertical	Horizon.	3 Axes	4 Axes	5 Axes	One	Two			Manual	CNC
1	0	1	1	0	0	1	0	0	0	1	0
2	1	0	1	0	0	1	0	0	0	1	0
3	0	1	1	0	0	1	0	0	0	0	1
4	0	1	0	1	0	1	0	0	0	0	1
5	1	0	0	1	0	0	1	1	1	0	1
6	0	1	0	0	1	1	0	0	0	0	1
7	1	0	0	0	1	1	0	1	0	0	1

Figure 2.10: Case study: manufacturing capabilities (Kashkoush & ElMaraghy, 2017)

Part	Product features											
	1		2			3	4			5		6
	Dimentionality		Shape			Rotational feature	Machined surface			Special surface		Auxiliary holes
	Rail	Cube	Rectangular	Non Rec.	Compound		One Dir.	Stepped	More	Keyway	Complex	
1	0	1	1	0	0	0	1	0	0	0	0	0
2	0	1	1	0	0	0	1	0	0	1	0	0
3	0	1	0	0	1	0	0	1	0	0	0	0
4	1	0	0	1	0	0	0	0	1	0	0	0
5	0	1	0	0	1	1	0	1	0	0	1	1
6	1	0	0	1	0	0	0	0	1	0	1	0
7	0	1	0	0	1	1	0	0	1	0	1	0

Figure 2.11: Case study: product features (Kashkoush & ElMaraghy, 2017)

The aim of the model is, of course, to associate these two dimensions. The association matrix from the AlGeddawy and ElMaraghy (2011) case study is shown in Figure 2.12.

			Product Features											
			1. Dimentionality		2. Shape			3. Rotational Feature	4. Machined Surface			5. Special Surfaces		6. Auxiliary Holes
			Rail	Cube	Rectangular	Non Rec.	Compound		One Dir.	Stepped	More	Keyway	Complex	
Manufacturing Capabilities	1. Structure	Vertical	0	0	0	0	0	1	0	0	0	1	0	0
		Horizontal	0	1	0	1	0	0	0	0	0	0	0	0
	2. Axes of Motion	3 Axes	0	1	0	0	0	0	0	0	0	0	0	0
		4 Axes	0	0	0	0	0	0	0	0	1	0	0	1
		5 Axes	0	0	0	0	0	0	0	0	0	0	1	0
	3. No. of Heads	One	0	0	0	0	0	0	1	1	1	0	0	0
		Two	0	0	0	0	0	0	0	0	0	0	1	0
	4. Turning Spindle		0	1	0	0	0	0	0	0	0	0	0	0
	5. Turret/Tool Mgazine		0	0	0	0	0	0	0	1	0	0	0	0
	6. Control	Manual	0	0	1	0	0	0	0	0	0	0	0	0
		CNC	1	0	0	0	1	0	0	0	0	0	0	0

Figure 2.12: Case study: association matrix (Kashkoush & ElMaraghy, 2017)

AlGeddawy and ElMaraghy's (2011) propose also another way to visualize the association between machine capabilities and product features (Figure 2.13). Each product feature is listed along with its respective machine capability. This method is especially useful when new products (with new product features) need to be implemented in production, significantly reducing the time required to develop the product (Kashkoush & ElMaraghy, 2017).

1. Dimentionality:	Rail	→	Control: CNC
	Cube	→	Structure: horizontal
			Axes of motion: 3 Axes
			Turning spindle
2. Shape:	Rectangular	→	Control: manual
	Non-rectangular	→	Structure: horizontal
	Compound block	→	Control: CNC
3. Rotational feature		→	Structure: vertical
4. Machined surface:	One direction	→	No. of heads: one
	Stepped surface	→	No. of heads: one
			Turret/Tool magazine
	More direction	→	Axes of motion: 4 Axes
			No. of heads: one
5. Special surfaces:	Keyways/grooves	→	Structure: vertical
	Complex surfaces	→	Axes of motion: 5 Axes
			No. of heads: two
6. Auxiliary holes		→	Axes of motion: 4 Axes

Figure 2.13: Case study: manufacturing capabilities associated with each feature (Kashkoush & ElMaraghy, 2017)

Compared to most of the methods discussed in the previous sections, the integer programming model is simple, easy to implement and automate (Kashkoush & ElMaraghy, 2017). It is simpler than the cladistic model, it does not generate redundant results that need to be discarded through further steps, and requires less implementation and development efforts (AlGeddawy & ElMaraghy, 2010; Kashkoush & ElMaraghy, 2017).

2.3.1.6 Information model from Dantan et al. (2008)

Dantan et al. (2008) propose an information model which collects data on KPFs, KMCs and their interrelations. The model (Figure 2.14) consists of four steps:

1. The first step involves the evaluation of customer functional requirements and the identification of the functional characteristics.
2. The second step concerns the technical functional analysis of the product defined in the previous phase. The product structure, its functionalities and constraints are carefully analyzed.
3. During the third step, the product is broken down into parts and the KPFs are identified. In this phase, the tolerances, material, geometry, dimension are specified.
4. The last step involves the decision of optimal manufacturing processes, thus the selection of optimal machines according to the specifications determined with the previous steps.

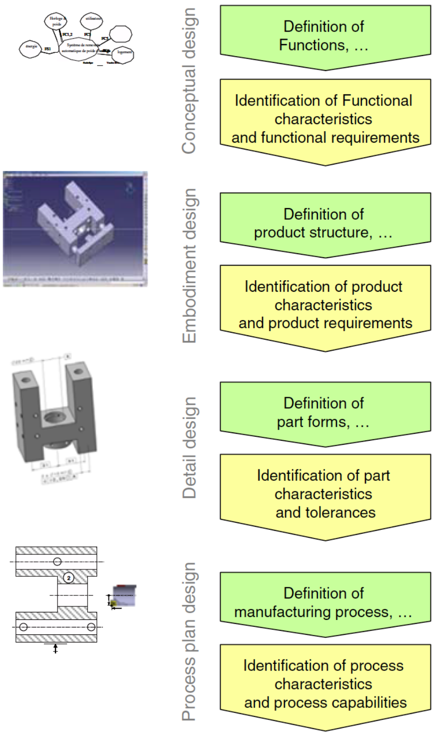


Figure 2.14: Information model (Dantan et al., 2008)

2.4 Quality analysis

Geometrical variations are inevitable problems in manufacturing, even if manufacturing processes and measurement techniques have reached a high level of reliability (Hallmann et al., 2020). Phadke (1989) claims that the causes of variation in manufacturing processes can be categorised into three types:

- External or noise factors, which are concerned with the environment of the machining process.
- If multiple parts are subjected to machining during the same time interval.
- Deterioration of machine tools.

For products made of several parts, when the final product is assembled, the variation propagates and grows exponentially (Lööf et al., 2007). Therefore, accurate tolerance allocation on each part is of crucial importance. Generally, the outcomes of geometrical variations are non-compliant quality standards, functionality imperfections and high costs, e.g., rework, repair, adjustment and scrap costs (Hallmann et al., 2020). This is the reason why tolerances for each product feature must be carefully specified, so that geometrical and quality standards are met, ensuring that geometry variations fall within a specific variation range in respect to the nominal value (Hallmann et al., 2020). Tolerance is the specification that defines the maximum geometric variation allowed (Wärmefjord et al., 2020). However, traditional tolerance allocation methods are often time consuming and expensive, due to their unmethodical and ununified approaches (Hallmann et al., 2020). In order to allocate tolerances in a more systematic way, which takes into consideration both geometrical variations and costs, Hallmann et al. (2020) propose the adoption of a mathematical optimization approach, consisting of optimization techniques aimed at balancing the two main conflicting objectives when it comes to tolerances, i.e., costs (possibly reduce them as much as possible) and quality (possibly increase it as much as possible). Hallmann et al. (2020) define tolerance optimization as an approach aiming at achieving “an optimal tolerance allocation by selecting a set of tolerance values while the tolerance specification is fixed” (p. 4862). In addition, to achieve an optimal tolerance allocation, tolerance-cost optimization takes also into consideration the cost dimension (Hallmann et al., 2020). The need of a tolerance-cost optimization approach is motivated by the frequent habit of allocating tolerances only based on the product functionality, thus ignoring the impact of costs. This determines high quality standards, but at the expense of very high costs (Hallmann et al., 2020). A sweet spot between the two dimensions must be found (Figure 2.15).

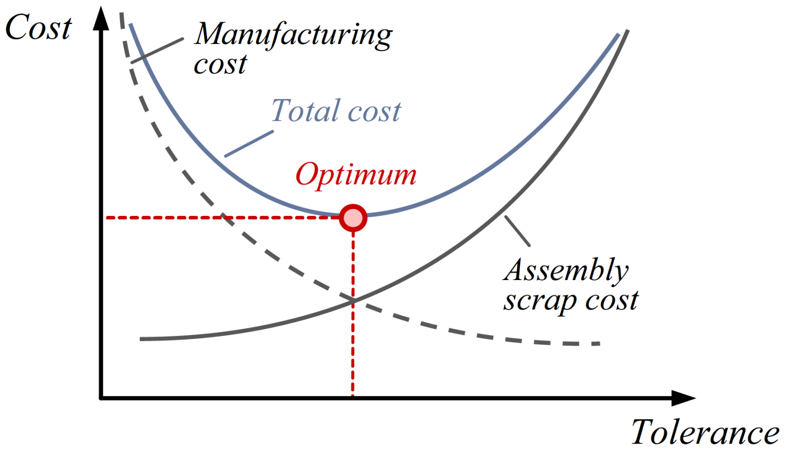


Figure 2.15: Sweet spot between tolerance and cost (Hallmann et al., 2020)

The starting point when it comes to tolerance allocation is the identification of the critical characteristics of the product, the KPFs presented in Section 2.2.1 (Hallmann et al., 2020). The fulfillment, in terms of variation control, of the set of all KPFs ensures the compliance with the product requirements. Each quality requirement is expressed as design information, i.e., geometrical requirement, and translated into KPFs. Then, locating points are assigned to improve robustness (Söderberg et al., 2016). Afterwards, tolerance types are specified for each KPF and values (ranges of deviation from target values) are assigned to them. Nevertheless, the correct identification and proper tolerance allocation to KPFs is a complex task that requires an advanced product and process experience (Hallmann et al., 2020).

2.4.1 The aerospace sector

In the aerospace sector, quality is the main critical concern. High quality and safety standards are demanded, hence manufacturing variations must fall within a very narrow margin (Madrid et al., 2016). Fabrication, the process of welding small parts together to create large and complex products, is the current trend for machine processes in the aerospace industry. To reduce the weight of the engine components, fabrication processes are used more than large castings and forgings. The main drawback of using this process lies in the exponential increase in the sources of variation (Madrid et al., 2016).

2.4.2 Geometry assurance and locating schemes

Geometry assurance refers to all the methods and actions aimed at ensuring that products fall within certain tolerance ranges and that the negative effects of geometric variations are reduced (Söderberg et al., 2016). Wärmefjord et al. (2014) assert that an effective method to reduce the negative effect of geometry variations is the accurate and robust definition of locating schemes. Wärmefjord et al. (2014) define locating schemes as the set of physical locators that “fixate parts in space during manufacturing and joining operations and control how variation propagates in the assembly" (p. 1401). The aim of locating schemes is to block a part/product in the space by locking its degrees of freedom (Söderberg et al., 2016). For a rigid part/product, the locating scheme is designed by assigning six points, which in turn lock the part/product's six degrees of freedom. When it comes to non-rigid parts/products, this number must be increased by locating supplementary points (Wärmefjord et al., 2014). In this case, Computer Aided Tolerancing (CAT) software can be used to handle increased complexity (Söderberg et al., 2016). To avoid including additional geometry variations, it is suggested to not change locating scheme during the three main production phases, i.e., manufacturing, inspection and assembly (Söderberg et al., 2016). In practice, the locating points are made to coincide with specific KPFs, e.g., holes, slots, etc. (Wärmefjord et al., 2014). The robustness of the locating scheme, which in turn ensures the minimization of geometry variation and secures functionality, can be enhanced by spreading the locating points in the largest possible area (Söderberg et al., 2016).

Fixturing strategies have a significant and direct effect on geometrical variation (Wärmefjord et al., 2014). Fixtures are important holding devices that ensure that the correct position and orientation of the workpiece is maintained during machining operations (Fan & Kumar, 2010). Therefore, errors in the layout of fixturing devices directly affect the overall machining errors on the workpiece (Vishnupriyan et al., 2010). It is important to make sure that the layout of fixturing elements is optimized and be aware that different fixturing strategies result in different tolerance outcomes (Wärmefjord et al., 2014).

In the context of Industry 4.0, and through the new tools brought by the digital revolution, Wärmefjord et al. (2020) propose the implementation of digital twins to optimize and manage geometrical variations in production. The success of the implementation of digital twins for geometry assurance is shown by the Wärmefjord et al. (2020) research, which demonstrates a reduction of more than 50% of geometric variations for the assembly operations. The main drawback to the implementation of digital twins for variation management is the current difficulty of updating and sharing 3D models (Wärmefjord et al., 2020). One way to overcome this problem is to use neutral files, such as the STEP standard presented in Section 2.2.1.3.2.

2.4.2.1 Uncoupled and coupled positioning of features

An essential difference when it comes to controlling the position of KPFs must be made between uncoupled and coupled positioning. Figure 2.16 shows the difference in the case of hole positioning. With the uncoupled method, the position of each hole refers to the same reference position (in this case the left side of the part). With the coupled method, the position of each hole refers to the position of the other holes. The latter approach exponentially increases the propagation of geometric variation. Therefore, the uncoupled method is preferred (Wärmefjord et al., 2014).

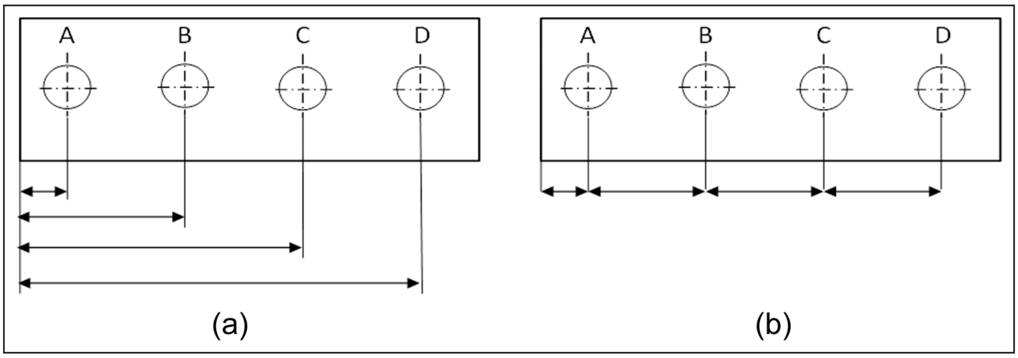


Figure 2.16: Uncoupled (a) and coupled (b) positioning of features (Wärmefjord et al., 2014)

2.4.3 Machining accuracy

Weck (1984) claims that machining accuracy is reliant on the four characteristics listed in Table 2.4.

Table 2.4: Machining accuracy characteristics (Weck, 1984)

Characteristic	**Detail**
Temperature influence	The geometric dimensions of both the workpiece and the machine tool alter when temperature varies during time.
Geometry and kinematic	This category comprises the relative motions between the workpiece and machine tool. Geometric involves variations, inaccuracies and errors that occur when positioning machine capabilities, e.g. axes, fixtures, etc. Kinematic involves variations, inaccuracies and errors that occur when moving machine components, e.g., spindle motion, to perform machining operations.
Static stiffness	It represents the strength of a machine to static loads, e.g., gravity, cutting forces, etc., before accuracy is compromised.
Dynamic stiffness	It represents the strength of a machine to dynamic loads, i.e., vibrations, before accuracy is compromised.

2.4.4 Statistical quality control

Statistical methods can be used to monitor and ensure compliance with quality standards.

2.4.4.1 Process capability indexes

Process capability is a statistical approach that provides numerical measures to analyze the outcome of a process with regards to certain specification limits (Mottonen et al., 2008). It is defined as the ability of a process to perform machining operations within a certain tolerance range, under the influence of changes and variations (Larsson, 2002). The process capability index Cp is defined as:

$$Cp = \frac{USL - LSL}{6\sigma}$$

Where USL is the Upper Specification Limit, LSL is the Lower Specification Limit and σ is the process standard deviation (Larsson, 2002). Cp is the basic version of the process capability index. There are several variants of it widely used today. One of them is the corrected process capability index Cpk, which derives from Cp, but takes into account how the process deviates from the USL or LSL only. Cpk uses the process mean, without considering the whole range of specification but half of it (Bottani et al., 2021).

$$Cpk = min \left| \frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma} \right|$$

Where μ is the process mean (Larsson, 2002).

Capability analysis through Cp and Cpk indices provides deep knowledge of the state of the production system and its changes (Katikar & Shinde, 2012). The main constraint when applying these indices concerns the statistical distribution to which they refer. Cp and Cpk indices are valid and can be fully utilized only if the population of data values is normally distributed and the process is statistically controlled, i.e., the process variation is symmetrical (Mottonen et al., 2008). When the process distribution is not normal, methods to transform the data values from a non-uniform distribution into a normal distribution can be used (Larsson, 2002). This ensures the applicability of Cp and Cpk indices even in cases where the process distribution is not normal.

2.4.4.2 Process capability values

As a rule of thumb, the higher the value of the process capability, the better the process performance is (Larsson, 2002). A process is considered capable when the process capability index is greater than 1 (Bottani et al., 2021). Nonetheless, a value of 1.33 is generally considered to be the minimum requirement of acceptance. Values below 1 are categorized as not acceptable, because compliance with tolerances is not guaranteed (Larsson, 2002). In any case, the process capability value is strictly dependent on the value of the two specification limits, as can be seen from the formula below:

$$Cp = \frac{USL - LSL}{6\sigma}$$

When the tolerance requirement is not strict, the value of the numerator of the Cp formula increases, therefore the Cp value increases accordingly (Larsson, 2002).

By referring to the process capability index, the quality condition of the process can be classified as shown in Table 2.5 (Katikar & Shinde, 2012).

Table 2.5: Quality condition in relation to the Cp value (Katikar & Shinde, 2012)

Quality condition	**Cp value**
Inadequate	$Cp < 1.00$
Capable	$1.00 \leq Cp \leq 1.33$
Satisfactory	$1.33 \leq Cp \leq 1.50$
Excellent	$1.50 \leq Cp \leq 2.00$
Super	$Cp > 2.00$

2.5 Cost analysis

In today's global market, ensuring high quality, reducing lead times and estimating costs are requirements that guarantee the success of companies. The high pressure for cost reduction has given even more importance to cost analysis (Roy et al., 2011). The assessment and estimation of costs are crucial activities to ensure the calculation of the aggregated cost of a product/service produced by a specific production system. However, not only the costs directly related to the product must be taken into consideration, but also the factors that affect the cost of the entire production system, such as costs to support production operations (Windmark & Andersson, 2015).

There exist several approaches to evaluate the costs of production systems. Cooper and Kaplan (1988) propose an activity-based costing model, which considers as product costs all the activities that contribute to the product realization. Cooper and Kaplan (1988) separate product costs into:
- Logistics
- Production
- Marketing and sales
- Distribution
- Service
- Technology
- Financial administration
- Information resources
- General administration

Aderoba (1997) proposes a revisiting of the activity-based costing model, based on a more general classification of activities. In this case, the model classifies the activities into the following categories:
- Machine-based production
- Labor-intensive production
- Technical services
- Administrative services

When carrying out the cost analysis, for some industry sectors such as the aerospace industry, the amount of tied-up capital plays a very relevant role (Windmark & Andersson, 2018). Windmark and Andersson (2018) propose a model according to which the final production cost is calculated by combining all the individual costs that occur when value is added to the product. To take into account all the value adding elements, Windmark and Andersson (2018) propose the model depicted in Figure 2.17. According to this approach, the cost analysis starts just after the material is stored in the company warehouse and ends with the storage of the material produced and waiting to be shipped (Windmark & Andersson, 2018).

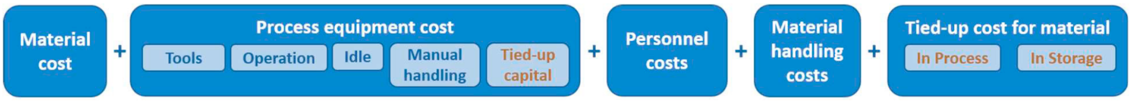


Figure 2.17: Cost elements (Windmark & Andersson, 2018)

Roy et al. (2011) propose a comprehensive approach to evaluate costs, based on three dimensions (Figure 2.18):

1. The first dimension represents the cost for raw materials.
2. The second dimension is the value-adding operations performed by manufacturing resources (both machines and humans).
3. The last dimension identifies all the other costs determined by the other activities not included in the previous categories.

Roy et al. (2011) stress the importance of the data and information gathering process for this approach, as “a credible cost estimate is formulated by selecting the appropriate cost information from a vast store of knowledge and information resources” (p. 697).

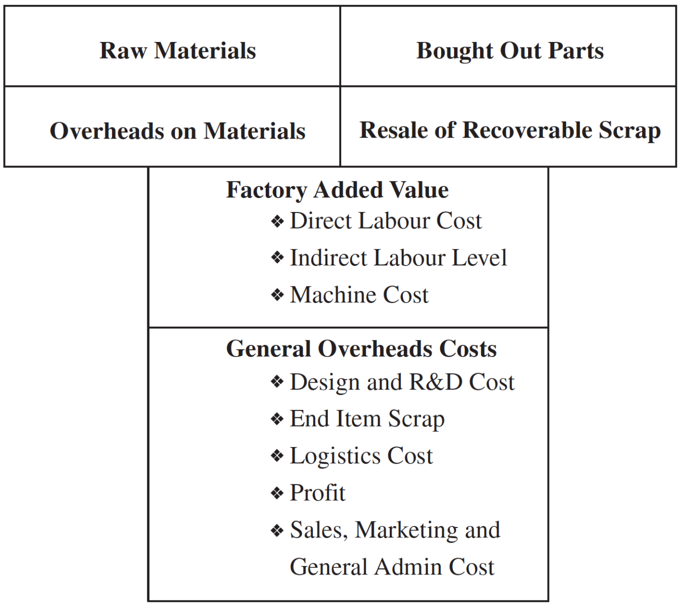


Figure 2.18: Cost elements (Roy et al., 2011)

2.6 Sustainability

The Brundtland Commission, alias the World Commission on Environment and Development (WCED), defines sustainability as “development that meets the needs of the present generation without compromising the ability of future generations to meet their needs” (Thomsen, 2013, p. 2358). This definition must be adapted to the manufacturing environment. UMass Lowell (2021), the University of Massachusetts Lowell, defines sustainable production as “the creation of goods and services using processes and systems that are:

- Non-polluting
- Conserving of energy and natural resources
- Economically viable
- Safe and healthful for workers, communities, and consumers
- Socially and creatively rewarding for all working people” (p. 1).

Nowadays, due to frequent changes in production, product life cycles are becoming shorter. Consequently, the life cycle of production systems is shortened accordingly. This new trend requires adapting such production systems and ensuring that all manufacturing capabilities of the current production system are fully utilized before introducing new ones. This means accurate evaluation and utilization of existing manufacturing capabilities before introducing new resources. This translates into a durable environmental and economic sustainable benefit, by optimizing the utilization of the existing production system and managing to produce more and better (AlGeddawy & ElMaraghy, 2012). Nowadays, reducing energy consumption and carbon footprint are a necessity in the manufacturing environment (Battaïa et al., 2020). Wang and Li (2013) show that industry is the main energy consumer among all business sectors, hence the one that pollutes the most. The design and development of production systems need to be reconceived. Globally, something is changing, for example many manufacturing companies are starting to rely more on renewable energies. However, renewable energies open to supply problems due to their unreliable characteristics. Therefore, from the energy supply perspective, production systems need to be designed in a flexible way, e.g., by using smart grids where in the event of a sudden lack of an energy resource, it is possible to switch on another resource that coexists on the same grid (Battaïa et al., 2020).

2.6.1 The Triple Bottom Line (TBL)

To ensure a comprehensive evaluation, sustainability needs to be assessed from three perspectives. Not just the traditional economic profit that companies generate should be assessed, but also the impact that they generate both on the environment and on society. This broad approach to sustainability is commonly defined as Triple Bottom Line (TBL) (Figure 2.19) (Lewis & Slack, 2017). Lewis and Slack (2017) define sustainable business from the TBL approach as “the one that creates an acceptable profit for its owners, but minimises the damage to the environment and enhances the existence of the people with whom it has contact. In other words, it balances economic, environmental and societal interests” (p. 51).

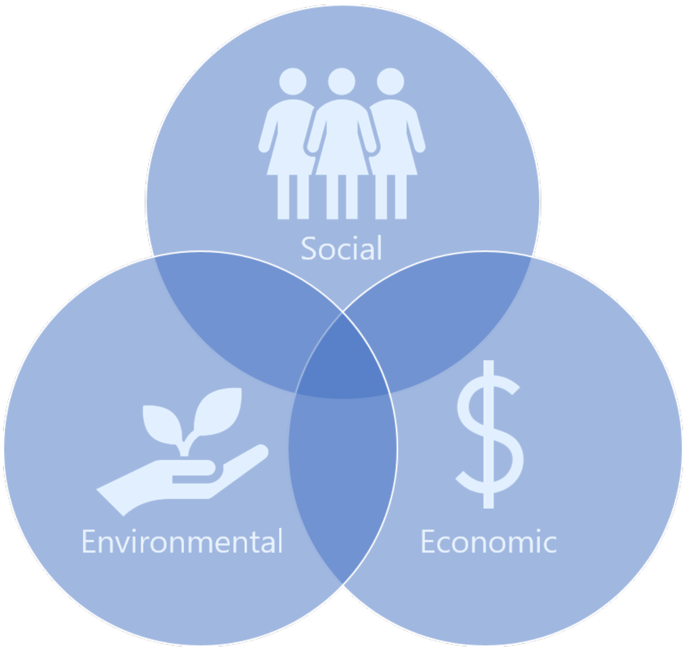


Figure 2.19: Triple Bottom Line (TBL) (SAI, 2021)

Even in the manufacturing environment, sustainability needs to be evaluated from these three perspectives:

- Environmental sustainability in manufacturing means reducing the use of natural resources and energy consumption, increasing the material recycling, reducing pollution and harmful emissions, reducing transportation activities and all non-value adding operations, thus reducing the environmental impact (Battaïa et al., 2020; Lewis & Slack, 2017).
- Economic sustainability in manufacturing lies in creating profit for everyone and ensuring constant development and competitiveness (Battaïa et al., 2020).
- Social sustainability in manufacturing means boosting social development, reducing social differences and improving working conditions, e.g., through the introduction of new means to lighten hard jobs, reducing alienating works and making dangerous jobs safer (Battaïa et al., 2020; Lewis & Slack, 2017).

2.6.2 Sustainability in the aerospace industry

Nowadays, in the aerospace industry, the reduction of CO2 emissions is of primary importance (Madrid et al., 2016). Many areas contribute to this challenge: material science, manufacturing processes, design technologies, etc. (Vallhagen et al., 2013). Weight reduction is the primary medium that can be used to pursue this purpose (Madrid et al., 2016). Moreover, new manufacturing approaches can play a central role to meet this challenge. For instance, by adopting fabrication (i.e., assembling sub-components together) instead of the well-known casting or forging methods, a significant reduction in engine weight can be achieved (Vallhagen et al., 2013). Compared to casting and forging, fabrication ensures larger design possibilities, optimizing geometries and eventually weight (Madrid et al., 2016). Sustainable assessments are becoming more and more popular among companies to evaluate their programs time to time, in order to check if they are aligned towards sustainable goals (Strömberg & Ramchandran, 2014).

2.6.3 Relationship between flexibility and energy consumption

The manufacturing industry is recognized as one of the most energy-consuming sectors. Energy consumption negatively affects not only the environmental impact, but also the economic sustainability, as energy has been shown to be the highest cost of the manufacturing process and one of the highest costs (together with the transportation cost) in the entire life cycle of the product (Storck, 2012). Storck (2012) demonstrates how flexible production systems improve the speed of the entire manufacturing process, reducing queues and lead times, thus reducing energy consumption. There is a close connection between product variants, production system's flexibility and energy consumption. Large product variety leads to an increase in energy consumption because set-up and lead times increase exponentially. However, the more flexible the production system, the lower the energy consumption. The reason is that, when having a flexible production system, short set-up times allow faster and more effective production changes, guaranteeing high production capacity (Storck, 2012). As a consequence, the use of queues and buffers is drastically reduced.

2.6.4 RMS and sustainability

RMS discussed in Section 2.1.4.1 is a successful approach to manage variations and changes in production, keeping high quality standards and moderate cost (Najid et al., 2020). However, this is not all. RMS represents a solution for the implementation of sustainable production systems, aimed at optimizing lead time and reducing energy consumption. The RMS nature of adaptability, reconfigurability and scalability allows to quickly switch and select the most appropriate, and expectedly the most sustainable and efficient, energy configuration (Battaïa et al., 2020). RMS and sustainability are tightly related to each other. The RMS's main objective is the optimization of resource usage, which is a concept that directly affects environmental and economic sustainability (Battaïa et al., 2020). An interesting implication for sustainability discussed by Battaïa et al. (2020) is the disposal of the RMS at their end of life. The intrinsic nature of modularity of RMS allows it to reuse some modules (or parts) of the production system, or to recycle the materials used for it (Battaïa et al., 2020). It becomes a sort of circular economy, where some modules of the production system are reused or recycled, hence reducing waste and consumption of new materials and natural resources. Figure 2.20 shows the possible options for the end-of-life treatment of a RMS.

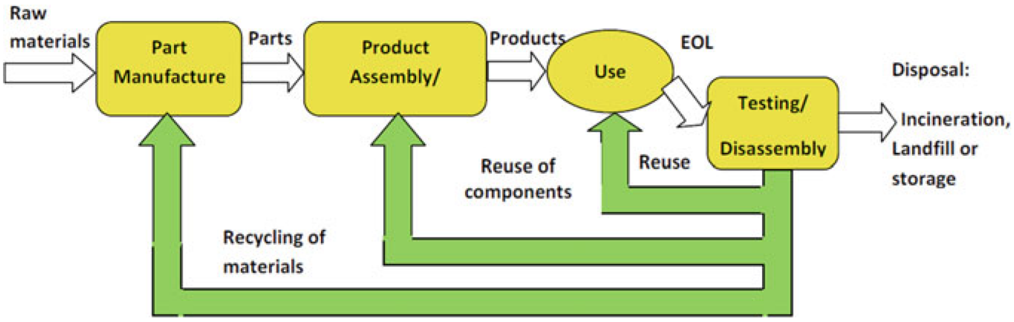


Figure 2.20: Possible options for disposal of the RMSs at the end of their life cycle (Battaïa et al., 2020)

3

The jet engine

This chapter presents the basic functioning of a jet engine. The information was collected from both literature and qualitative data. The text and figures without references come from interviews and GKN Aerospace internal documents.

3.1 The basic functioning

The products of interest for this project are the Turbine Exhaust Case (TEC), Low-Pressure Turbine (LPT) case and Intermediate Compressor Case (ICC), all part of the jet engine. To properly understand their basic functioning, a simple description of the principles of a jet engine needs to be provided. The jet engine generates thrust in accordance with Newton's third law of motion, demonstrating that every action produces a reaction equal in force and opposite in direction.

Commercial jet engines are divided into two types, based on the number of shafts present:
- Two-shafted engines, where one shaft connects the Low-Pressure Compressor (LPC) and Low-Pressure Turbine (LPT), and the other connects the High-Pressure Compressor (HPC) and High-Pressure Turbine (HPT) (Nytomt & Persson, 2002).
- Three-shafted engines, which have two shafts as discussed above, plus an additional shaft connecting the Intermediate-Pressure Compressor (IPC) and Intermediate-Pressure Turbine (IPT) (Nytomt & Persson, 2002).

The information that follows is based on the two-shafted jet engine.

The functioning principle of a jet engine consists of four main steps (Figure 3.1):
1. The air intake is an opening placed in front of the engine that allows the air at ambient pressure to enter the LPC.
2. During the compression stage, the air at ambient pressure is compressed to a desired pressure. The compressor is made of a number of stages. Each stage is made of a vane that rotates and a vane that remains stationary. When compressing a fluid, its pressure, hence the temperature, increases. The energy needed to compress the air is obtained from the LPT (connected to the LPC).
3. The combustion takes place by mixing the compressed air with the fuel in the combustion chamber.
4. The compressed air temperature increases continuously, leading to volume

expansion. This air escapes out of the engine via the turbine by producing the thrust, thus generating energy (Nytomt & Persson, 2002). Part of this energy is used by the LPC, connected to the LPT via a shaft. The exhaust gases pass through the nozzle, thus generating thrust.

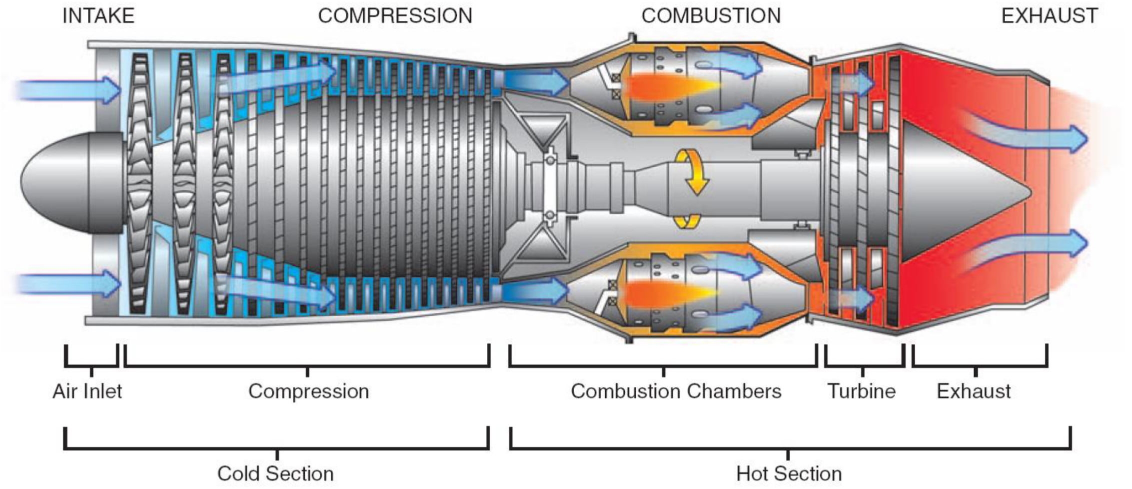


Figure 3.1: The four functioning steps of a jet engine (from GKN Aerospace internal documents)

The major components of the jet engine can be categorized into two sections:

- The cold section comprises the air inlet and compressor.
- The hot section comprises the combustion chamber, turbine and exhaust.

It is important to notice that the description above only applies to pure jet engines, i.e., jet engines where the whole thrust is obtained with the airflow passing through the core (principal/central) channel. Nowadays, it is quite common to use an additional airflow channel, called bypass, which passes through a duct fan (Nytomt & Persson, 2002). The bypass provides a larger amount of thrust compared with the previous case, at the expenses of increased complexity of the system. Figure 3.2 shows an overview of the components of a jet engine.

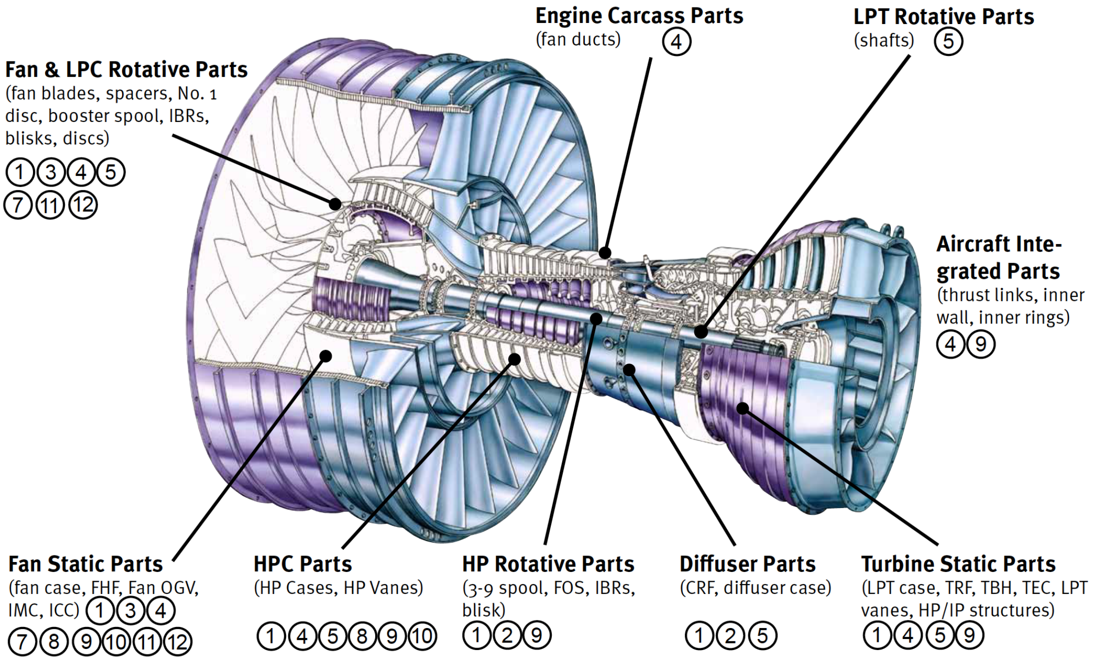


Figure 3.2: The components of a jet engine (GKN Aerospace Engine Systems HQ, 2016)

3.2 Low-Pressure Turbine (LPT) module

The Low-Pressure Turbine (LPT) module is located in the rear end part of the jet engine. It is powered by the exhaust gases coming from the HPT. The LPT, in turn, powers the LPC through the low-pressure shaft. The LPT is made of several stages of two elements: rotor and stator. Rotors are connected to the low-pressure shaft and rotate at high speed. Stators are fixed to the LPT case. The LPT module comprises:

- LPT rotors
- LPT stators
- LPT case
- Turbine Exhaust Case (TEC)

3.2.1 LPT case

The LPT case is a thin wall barrel shaped structure (Figure 3.3), made of a single material by forging or casting and then machined into the inner profile to create specific features (Germano, 2006). It has several functions:

- Keep stator blades fixed to the LPT case body and in correspondence to the rotor blades. This allows keeping the air flow parallel to the axial direction of the engine.
- Protect the jet engine in the case of detachment of blades, thus preventing them from leaving the case.
- Withstand the thermal stresses typical of the jet engine.
- Transmit thrust loads.

Figure 3.3: LPT case (Runnemalm & Alberg, 2007)

3.2.2 Turbine Exhaust Case (TEC)

The Turbine Exhaust Case (TEC) is part of the LPT module, located at the rear end of the jet engine (Figure 3.4) (Otto et al., 2013).

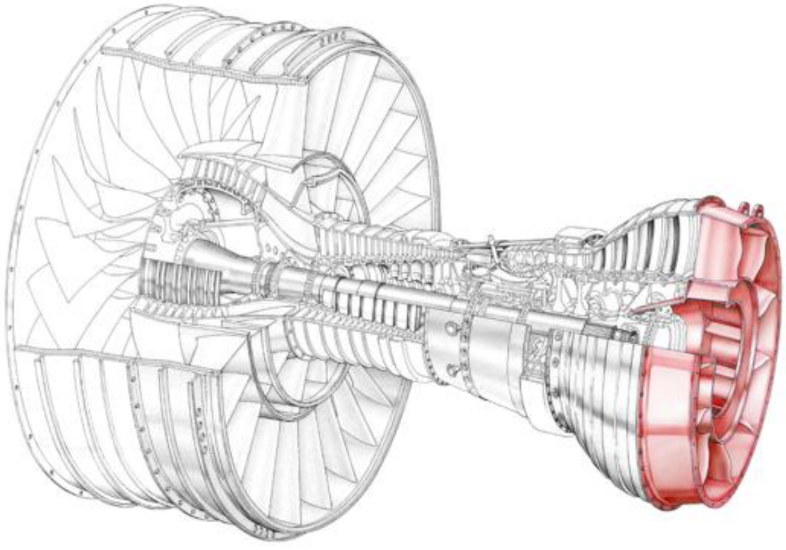


Figure 3.4: TEC (marked in red) (Otto et al., 2013)

It is called Turbine Exhaust Case (TEC), Turbine Rear Frame (TRF) or Tail Bearing Housing (TBH) depending on the manufacturer. The product of interest for this project is the "solid" structure of the TEC, i.e., the structural part with the exclusion of the tube system, fasteners, brackets, etc. The TEC structure can be seen as a set of modules that are welded together (Andersson & Petersson, 2015). Three parts make up the structure of these modules: an outer case, several struts (or vanes) and an inner ring (called hub) (Figure 3.5) (Andersson & Petersson, 2015).

The outer case can be of two different types, regular and mount, depending on the functionality and design characteristics (Andersson & Petersson, 2015). These parts are welded together using panels (Tingelstad & Egeland, 2014). Since all these modules must be welded together at the same time, thus the whole product must fit into the machine, the machine accessibility needs to be carefully evaluated.

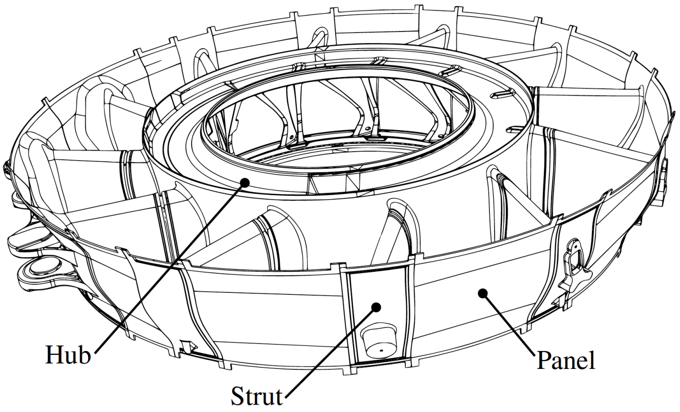


Figure 3.5: The TEC "solid" structure (Tingelstad & Egeland, 2014)

The main function of the TEC is the structural support to fix the engine to the aircraft's body (Andersson & Petersson, 2015). Other important functions are:

- Withstand high temperatures and loads.
- Provide the air stream with a proper discharge path, to create adequate propulsion.
- Reduce the air flow's swirl at the exit of the TEC to maximize propulsion.
- Contain the engine mounts to hold the turbine rear structure to the airplane's body.
- Provide structural support to the bearing.
- Ensure correct positioning of tubes with oil and air, cables and tubes for instrumentation.

3.3 Intermediate Case (IMC) and Intermediate Compressor Case (ICC)

The intermediate case is a structural component of the compressor module (Nytomt & Persson, 2002). In a two-shafted jet engine, this supporting structure is placed between the LPC and HPC and takes the name of Intermediate Case (IMC) (Figure 3.6); in a three-shafted jet engine it is placed between the LPC and IPC and takes the name of Intermediate Compressor Case (ICC) (Figure 3.7) (Nytomt & Persson, 2002).

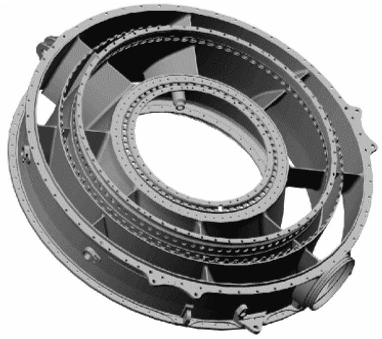


Figure 3.6: IMC (Nytomt & Persson, 2002)

Figure 3.7: ICC (Peña, 2015)

The product of interest for this project is the "solid" structure of the ICC, as discussed for the TEC. Four parts make up the "solid" structure: an outer ring, several bypass struts, a splitter box, several core struts and an inner ring (Rajagopal, 2005). As for the TEC, all these parts are welded together at the same time.

The main purpose of the IMC/ICC is to ensure resistance and support to the engine, in order to transfer the thrust from the engine to the airframe (Nytomt & Persson, 2002). Other purposes of the IMC/ICC are:

- Ensure that lubricant reaches bearings.
- Ensure that the core and bypass airflows are kept separated.
- Divide the engine into modules to avoid burning the whole engine in case of fire.
- Provide structural support to surrounding components, ensuring that they are kept in place.
- Maintain the noise level in the engine.

4

Methods

In this chapter, the design of the literature review and data analysis is described. Quality criteria and ethical concerns are further included.

4.1 Introduction

A triangulation of methods, consisting of a literature review, a quantitative data study and a qualitative data study, was adopted for this research study (Figure 4.1). The purpose of the combination of these three studies is to provide a comprehensive understanding of the research area from as many perspectives as possible and answer the research questions as fully as possible (Olajide & Lawal, 2020). The triangulation of methods expresses its strength when it comes to avoiding bias and inconsistencies that are likely to arise when using just one method.

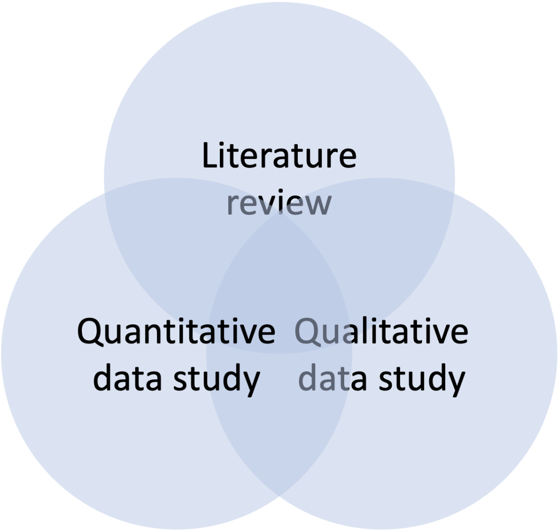


Figure 4.1: Triangulation of methods

The main part of the project was carried out remotely due to the current COVID-19 pandemic and in compliance with the regulations of the Public Health Agency of Sweden. Periodic meetings with the academic examiner and supervisor Kristina Wärmefjord, GKN Aerospace supervisor Stefan Cedergren (process engineer) and academic co-supervisor Sunney Fotedar were held through online conferencing platforms. The visits to the company site were arranged in advance with the GKN Aerospace supervisor, strictly following the regulations of the Public Health Agency of Sweden.

4.2 Literature review

The literature review is an essential part of the research as it constitutes the foundation for the whole project. It was used to overview the research area, gather background information on the main topics of the project and identify information that can complement quantitative and qualitative studies (Snyder, 2019). Several bibliographic databases were used to search for articles, books and other types of documents, such as ScienceDirect, ASME Digital Collection, SpringerLink, ResearchGate, Taylor & Francis Online, Harvard Business Review, etc. Specific keywords were considered to procure relevant documents through the databases (Table 4.1). The research results were further filtered to include only the most recent articles, to keep up with the recent updates in the field of technology and research (Snyder, 2019). Some documents were recommended and made available directly by the academic examiner and supervisor, GKN Aerospace supervisor and academic co-supervisor.

Table 4.1: Keywords used in the literature review

Keywords
Resource allocation
Production system
Product features
Machine capabilities
Aerospace
Standardization
Geometry assurance
Statistical quality control
Sustainability

4.3 Data analysis

The data analysis was based on the pairing of quantitative and qualitative data to broaden the depth of understanding and enhance the reliability, validity and credibility of the findings.

4.3.1 Quantitative data study

The quantitative data study was aimed to collect and analyze relevant data retrieved directly from GKN Aerospace. Mertens et al. (2017) define quantitative data analysis as “an iterative process of manipulating and interpreting numbers to extract meaning from them — answer research questions, test hypotheses, or explore meanings that can be derived inductively from the data” (p. 1). To delimit the analysis, only the data relating to three products that GKN Aerospace currently manufactures (TEC, LPT case and ICC) was collected; the data relating to the resources concerned only the machines potentially suitable for processing these three selected products. An Excel database containing the list of 39 machines, along with some of their specific properties and capabilities, was directly made available from the GKN Aerospace supervisor. This document, consisting of numerical data, was thoroughly assessed to derive as much information as possible about the resources to focus the study on. The data present in this document was analyzed, organized according to a specific structure and duplicates and mistakes were removed. The numerical data associated with the operations of two of the three products of interest was received from a GKN Aerospace CAM engineer and manufacturing engineer manager. Two Excel tables, one for each of the two products, were sent to the CAM engineers and filled in by themselves with the requested data.

4.3.2 Qualitative data study

Auerbach and Silverstein (2003) define qualitative data study as a “research that involves analyzing and interpreting texts and interviews in order to discover meaningful patterns descriptive of a particular phenomenon” (p. 13). The purpose of the qualitative data study was to fill in the gap left by the literature study and quantitative data study and collect in-depth information on both products and machines. For this project, the qualitative data study was aimed to collect and analyze information through periodic meetings, semi-structured interviews, questionnaires, documents, emails and company visits. Periodic meetings were held with the GKN Aerospace supervisor and academic co-supervisor to understand the products and machines in detail. The interview candidates were GKN Aerospace representatives covering different roles in the production environment, with extensive knowledge and experience. Interviews with production engineers and company visits were held to obtain a comprehensive understanding of the resources and products under consideration. Interviews with the manufacturing engineer manager, industrial engineer and CAM engineer at GKN Aerospace consisted of both video interviews and interviews at the company. An extensive exchange of documents with those roles took place. Wherever possible, interviews were recorded and transcribed to text. To structure the data, the transcripts and notes from the unrecorded interviews were analyzed and organized on separate notes. Thereafter, the qualitative data findings were combined with the quantitative data findings to provide a holistic view of the results.

4.4 Quality criteria

In this section, the approaches used to validate and ensure reliability and credibility of the project results are presented. The triangulation method was adopted to prevent bias and misinterpretations from arising when only one of the three studies is used. In general, all three studies were performed according to an established procedure defining the methods for collecting and analyzing the data and information. The three studies were all performed individually by both team members, who have different views due to different origins, backgrounds and experiences. No sections of the project were left to just one of the two team members. This assured accurate validation between the two different versions and perspectives. Only after brainstorming and debating the two versions, the final version of the sections was created. To prevent bias and misinterpretations of the data from being included in the final results, a constant review was carried out by the academic examiner and supervisor, GKN Aerospace supervisor and academic co-supervisor throughout the entire project period.

4.4.1 Literature review

To ensure validity and reliability, only reviewed and published articles were selected. Only reputed and credible databases were chosen for procuring the articles. Furthermore, wherever possible, recent articles were preferred, given the rapid technological development. The risk that the information retrieved through the literature review could be biased is twofold. On the one hand, the information could be misinterpreted by the literature reviewer. Inappropriate technical knowledge to understand and analyze the topic, or simply a superficial reading of the documents could negatively influence the correct understanding of the topic. On the other hand, literature reviewers may only include documents that support their perspective on the subject, thus excluding important findings (Grant & Booth, 2009).

In order to reduce conclusions that open up to bias, the whole process of the literature review was performed by both the team members individually. After finishing it, and after confirming the findings, the two individual versions of the literature review were combined, thus creating the final version. Additional support was given by the academic examiner and supervisor, GKN Aerospace supervisor and academic co-supervisor, to ensure that the information retrieved did not only support the team members' beliefs.

4.4.2 Quantitative data study

The data received from GKN Aerospace was analyzed and reorganized according to a structure suited to the approach of the project, duplicate data was removed and obvious errors in the data were analyzed and corrected with the help of the GKN Aerospace supervisor and CAM engineers. The numerical data concerning the machines and products were analyzed using a scientific approach and were never generalized. All the operations on the data were performed by both team members together, to reduce the chance of making mistakes and to minimize any bias based on individual beliefs. Data operations were performed with the close supervision of both the GKN Aerospace supervisor and CAM engineers, to ensure the correlation of data with reality.

The main problem encountered while performing the quantitative data study was the data availability. Since the developed approach heavily relies on data, the lack of data hindered the practical demonstration of how the approach works in practice. Nevertheless, by adopting alternative methods to procure the required data, e.g., by deriving the missing parameters from current allocations at GKN Aerospace, it was however possible to demonstrate the final findings with rigour and credibility, thus making the results as trustworthy as possible.

4.4.3 Qualitative data study

The qualitative data study was based on periodical meetings with the GKN Aerospace supervisor, academic co-supervisor and academic examiner and supervisor, interviews with GKN Aerospace engineers, questionnaires, documents, emails and company visits. All these activities were carried out by both team members. The team members were always present during the periodic meetings and interviews to ensure a broad and complete understanding of the information. The interviews were planned in detail and in advance. The questions for the interviews were first sent out to the GKN Aerospace supervisor for validation and then finalised based on his feedback. Interviews can be considered to be reliable as the interviewees were GKN Aerospace engineers who work directly with the products and machining operations of interest. However, interviewees may be biased in their answers for different reasons, e.g., they may only present their personal perspective, thus jeopardizing the evaluation of important information (Bailey & Jackson, 2003). To avoid bias, the project supervisor always participated in all the interviews to confirm and validate the information and to provide guidance and feedback. The resulting notes from meetings and interviews were written down individually by both team members and then discussed, confirmed and combined together. Documents containing qualitative data were first studied and analyzed individually by the team members and then discussed together, in order to decide how to use them. The same procedure applied to email communications and other methods of exchanging information. Both team members participated in all company visits to ensure a comprehensive understanding of the information and to minimize biased information.

4.5 Ethical concerns

Regarding the ethical aspects related to the methods with which the study was carried out, the project aimed at respecting and fulfilling the non-disclosure agreement with the company. Without the prior written consent of GKN Aerospace, sensitive data and confidential information were not included in the thesis work. The confidential information was used only for the purpose of working on the thesis project, not for private purposes. Sensitive and confidential data was analyzed exclusively on company laptops and never on personal laptops to ensure greater security. Each person interviewed during the project was asked for their consent to appear in the report. In case of lack of consent, anonymity was guaranteed. Respondents were also asked for consent to record interviews.

The project results were assessed by both team members, who have different points of view due to different origins, backgrounds and experiences, and by the company and academic representatives. To ensure that no bias or misinterpretation of the data are included, all conclusions were forwarded to the academic examiner and supervisor, GKN Aerospace supervisor and academic co-supervisor for confirmation.

5

Results

In this chapter, the analyses of both machine capabilities and product features are carried out. Thereafter, the results of these analyses are associated to find correlations between the two dimensions. The main result is a set of matrices showing the best match when it comes to allocating resources.

5.1 Introduction

The study contemplates two dimensions, i.e., products and machines. More specifically, product features (and the machining operations performed on them) and machine capabilities are analyzed in this study. The main result is the association of these two dimensions to pursue optimized resource allocation. The approach reflects the following structure:

- **Machine capabilities dimension**
  - Identification of the Key Machine Capabilities (KMCs) for the selected machines
  - Development of the “KMCs table”
- **Product features/operations dimension**
  - Identification of the Key Product Features (KPFs) for the selected products
  - Development of the “Operations table”
- **Association of the two dimensions to optimize resource allocation**
  - Compilation of the association matrices

The aim of this chapter is to show the approach underlying the project. The developed model is illustrated by means of a manual procedure using tables and matrices. However, to apply this approach to a real case, the manual procedure must be automated through programming and standardization. This aspect is further explored in Section 6.6.1.

Given the overall complexity of the method, the idea was to prefer a simplified approach when filling in the tables and matrices. This prompted the decision of choosing a binary approach involving only two possible values, i.e., 1 for a positive response and 0 for a negative response. There are some limitations to this adaptation, which are discussed in Section 5.2.1.

In the next sections, the concept of “job type” will be extensively used. In the present study, job type is defined as the combination of a given product feature with the machining operations performed on it (Fotedar et al., in press). There is a difference between job type and what GKN Aerospace defines as “operation”. Operation at GKN Aerospace refers to a set of job types, e.g., operation 1600 for the TEC includes two job types, i.e., the machining of the forward outer flange and the machining of the bearing house flange.

5.2 Key Machine Capabilities (KMCs)

The study analyzes 39 machines, belonging to three different workshops at GKN Aerospace. The capabilities of the machines of interest are identified and analyzed. Based on their impact on resource allocation, they are categorized into hard and soft constraints. Hard constraints represent requirements that must necessarily be met by the machines to perform the given operations on a specific product. Machine capabilities are also categorized into soft constraints, further divided into three levels to take into account the different nuances of requirements. If all the hard constraints are satisfied, the machine is qualified to perform the given operation on a certain product feature. If the soft constraints are met as well, the machining process can be improved from both quality and cost perspectives. Therefore, soft constraints (mainly level 2 and 3) would be preferable to be met, but they are not a must to qualify the machine.

In compliance with the non-disclosure agreement, and in order to avoid sharing sensitive data and confidential information, the actual names of the 39 machines are not included in the final work. Instead of their real names, machines are named as T for turning machines, M for milling machines and TM for multitask machines.

The machine capabilities are categorized in Table 5.1 and explained in detail below.

Table 5.1: Key Machine Capabilities (KMCs)

Level of constraint	**KMC**	**KMC state**
Hard	Machine structure	Vertical Horizontal
Hard	Dimensionality	Max diameter Height
Hard	Machining operation	Non-rotating (turning) Rotating (milling and drilling)
Hard	Tool magazine size	Non-rotating tools Rotating tools
Hard	Mass	Lightweight Heavyweight
Soft - Level 1	Axes of motion	-
Soft - Level 1	Dimensionality	Min Inside Diameter (ID)
Soft - Level 1	Internal milling head	Automatic tool change Speed Torque Under tilt Tool measurement (laser)
Soft - Level 1	External milling head	Programmable head Automatic tool change Speed Torque Under tilt Automated tool measurement
Soft - Level 1	Maximum tool length	-
Soft - Level 2	Coolant	Internal coolant pressure Internal coolant mid-jet Internal coolant high-jet
Soft - Level 2	Process capability (Cp)	-
Soft - Level 2	Tool measurement	Turning (contact probes) Milling (laser)
Soft - Level 2	Rotary table max speed	-
Soft - Level 2	Drilling spindle	Speed Tool measurement (laser)
Soft - Level 2	Number of touch probes	-
Soft - Level 2	Number of pallets	-
Soft - Level 2	Environmental factors	Noise generation Coolant hazard
Soft - Level 3	CNC generation	New Medium Old
Soft - Level 3	Machine age	Bought after 2005 (included) Renovated after 2015 (included)
Soft - Level 3	Machine verification	-

- **Hard constraints**
  - **Machine structure**
    It can be either horizontal or vertical. It is categorized as a hard constraint because it allows or prevents certain machining operations. For example, when machining flanges on products with large diameters, a vertical turning machine is required.

  - **Dimensionality**
    It represents the physical dimensions of the machine that allows or prevents the workpiece from fitting and being machined. For this case study, dimensionality is divided into maximum external diameter and height. The external diameter represents the maximum size of the machine in terms of diameter. The height represents the maximum size of the machine in terms of height. Both these capabilities ensure that the workpiece physically fits into the machine. Dimensionality is categorized as a hard constraint because it directly affects the possibility of machining a given product feature. This capability is highly dependent on the specific machining operation and is covered in more detail in Section 5.2.1.

  - **Machining operation**
    It represents the principal machining operation(s) that the machine can perform. For this case study, the two main machining operations are non-rotating (turning) and rotating (including milling and drilling). It is categorized as a hard constraint because it allows or prevents certain manufacturing results.

  - **Tool magazine size**
    The tool magazine is meant to store tools and allow for quick tool change in a machine. Based on the required machining operations, the tools in the magazine are categorized as non-rotating (turning) and rotating (milling and drilling) tools. It is categorized as a hard constraint because it ensures (or prevents) that specific operations can be carried out in the same machine. Since the number of tools present in the tool magazine is highly dependent on the specific machining operation, this capability is covered in more detail in Section 5.2.1.

  - **Mass**
    This capability checks the weight of the parts/products to be machined. Although it is not a critical capability for GKN Aerospace, as most parts/products are lightweight compared to parts/products of other industries of the same size (at GKN Aerospace the fixtures are usually heavier than the parts/products themselves), mass is categorized as a hard constraint. For this study this capability is left blank, but it is not excluded from the model as it can be used for future model updates.

- **Soft constraints**
  - **Axes of motion**
    It represents the number of axes of motion a machine has. A machine that is capable of performing drilling operations is automatically categorized as a three-axes machine; when it is not, it is categorized as a two-axes machine. It is also important to take into consideration if the machine simultaneously uses all five axes, or it just uses 3 + 2 or 4 + 1 axes. When performing full 5-axis machining, the three linear axes (X, Y, Z) and the two rotation axes (e.g., A, B) are all simultaneously engaged in the machining process. When performing 3 + 2 axes machining, only three axes are engaged in the machining operation and the other two axes are used to orient the cutting tool in a fixed position. When performing 4 + 1 axes machining, only four axes are engaged in the machining operation and the other one axis is used to orient the cutting tool in a fixed position. This machine capability is categorized as a level 1 soft constraint because, even if it is an important requirement, it is still possible to perform machining operations that require a certain number of axes on machines that do not reach them, e.g., by implementing additional features such as an external milling head. The number of axes of motion strictly depends on the specific machining operation and is covered in more detail in Section 5.2.1.

  - **Dimensionality (Inside Diameter (ID))**
    The Inside Diameter (ID) describes the capability of the machine to machine internal product features. ID is categorized as a level 1 soft constraint as, if there is any internal accessibility problem, an external milling head can be added to improve the access to the internal feature. This means that a KPF with small internal accessibility could be moved to a large machine if that machine has the external milling head capability. This capability is highly dependent on the specific machining operation and is covered in more detail in Section 5.2.1.

  - **Internal milling head**
    This capability includes all the critical parameters referred to machines having milling capability without adding separate milling heads, e.g., ordinary milling machines or multi-task machines. Whether the machine is equipped with a tool measurement system (laser) and automatic tool change is also taken into consideration. Under tilt represents the ability of the milling head to rotate and reach even negative angles while performing a certain machining operation. As an example, some A-axis machines allow for a lot of under tilt (approximately 65 degrees) and some B-axis machines allow for poor under tilt (approximately 1/2 degrees, maximum 3 degrees). The speed (rpm) and torque of the internal milling head are also taken into consideration and are covered in more detail in Section 5.2.1. The internal milling head capability is categorized as a level 1 soft constraint.

- **External milling head**
  It is an accessory that enables milling capability in turning machines, as well as changing machining directions of machines having internal milling heads, thus making the machining process more flexible. Milling machines can also be equipped with an external milling head to allow for better accessibility of critical features. Whether the external milling head is programmable, i.e., effectively adding one or more axes of motion, and thus enabling machining operations with directions other than fixed ones, is taken into account. If the machine is equipped with an automated tool measurement system (laser), automatic tool change and under tilt capability is also taken into consideration. The speed (rpm) and torque of the external milling head are also taken into consideration and are covered in more detail in Section 5.2.1. It is interesting to point out that, in some cases, it is also possible to machine internal features without adopting an external milling head, but relying on the internal milling head of a B-axis machine, positioning the internal milling head horizontally within the internal feature. This is made possible by the 45 degree inclination of the internal milling head of a B-axis machine, which allows the milling head to fit inside the internal feature without hitting the outer edges of the workpiece (which is likely to happen with an A-axis machine). The external milling head capability is categorized as a level 1 soft constraint because, even without this capability, it is possible to perform milling operations with other equipment or tools.

- **Maximum tool length**
  It is the maximum length of the tool that the machine can handle. It is categorized as a level 1 soft constraint as, when a part/product with a hard-to-access feature requires a long tool, the machine must be able to access long tools in its tool magazine to meet that requirement. It is also a critical factor when it comes to design the tool magazines. Since this capability is highly dependent on the specific machining operation, it is covered in more detail in Section 5.2.1.

- **Coolant**
  It describes the coolant type in terms of the pressure that the internal coolant system can withstand. The internal coolant pressure is directly dependent on the specific machining operation and is covered in more detail in Section 5.2.1. The internal coolant is also differentiated into mid- and high-jet. This capability is categorized as a level 2 soft constraint.

- **Process capability**
  It describes the capability of a certain machining process (performed on a particular machine) and its ability to fall within specified control limits. It heavily depends on both the specific customer requirements and the internal requirements of GKN Aerospace. A threshold value of 1 is generally considered acceptable. However, to obtain a more accurate pro-

cess, a threshold value of 1.33 is set. It is categorized as a level 2 soft constraint as machines that do not meet the higher process capability can still manufacture a given product, but the required quality standards cannot be entirely met.

- **Tool measurement**
  It concerns the automatic setting of tools' dimensions. For this specific case, two different tool measurement systems are considered, i.e., contact probes for turning tools and laser systems for milling tools. It is categorized as a level 2 soft constraint.

- **Rotary table max speed**
  The rotary table speed refers to machines with turning capability, thus controlling the achievable cutting speeds used on the workpiece. It is categorized as a level 2 soft constraint. Since this capability is highly dependent on the specific machining operation, it is covered in more detail in Section 5.2.1.

- **Drilling spindle**
  When a machine is equipped with a drilling spindle, it can perform drilling operations, such as machining blind holes, through bores or threaded holes. It is also considered whether the machine is equipped with a tool measurement system (laser). The drilling spindle speed (rpm) is a critical value. It is categorized as a level 2 soft constraint. Since this capability is highly dependent on the specific machining operation, it is covered in more detail in Section 5.2.1.

- **Number of touch probes**
  Touch probes are used for many functions, e.g., alignment of the workpiece, measurement and inspection of the workpiece, etc. Their number depends on the number of product features that need to be probed during the same machining operation. Therefore, the suitable number of touch probes must be set based on the specific machining operation. For this reason, this capability is covered in more detail in Section 5.2.1. It is categorized as a level 2 soft constraint because, even if the required number of touch probes is not present, the machine can be still qualified to carry out the required operation along with a manual check of the workpiece.

- **Number of pallets**
  It represents the number of exchangeable tables in the machine. When a workpiece is loaded in the machine, the whole table can be flipped, and another empty pallet is made available. It is a crucial capability because it decides the number of job types that can be performed at the same time, thus avoiding wasting time when changing fixtures. A threshold value of one pallet (commonly considered acceptable) has been set. It is categorized as a level 2 soft constraint because it directly affects produc-

tivity and costs.

- **Environmental factors**
  Employee's health and safety is one of the main priorities at GKN Aerospace. The environmental factors directly affect the workplace safety. They are divided into noise generation and coolant hazard. For example, machining operations that involve ceramic tools generate loud noise that directly affects the operators. In addition, some machining operations also require coolants and lubricants that might be hazardous for the operators. Although the environmental factors do not directly affect the machine output, if workplace accidents occur, they indirectly affect productivity and costs. They are categorized as a level 2 soft constraints.

- **Control system generation**
  It can be either manual or CNC, although the manual control system is not much used in the aerospace industry. Since none of the machines assessed have a manual control system, only the CNC is included. The CNC generation is divided into new, medium and old, depending on the time of introduction. The reason for this division is the difficulty and cost impact when it comes to shifting from a new control system to an old one and vice versa, mainly due to reprogramming and other compatibility problems. If this is the case, changing the entire process plan may be an option. When switching from a new to an old CNC, it may be necessary to do more operations manually, thereby increasing the process time. This might also affect the process capability (Cp) and the overall cost. It is categorized as a level 3 soft constraint.

- **Machine age**
  The machine's operating capacity decreases as it gets old. Therefore, it is necessary to take into consideration the age factor of the machine. This capability takes into consideration the year of introduction of the machine and also whether it has been recently renovated. A machine is considered new if it was introduced into the factory no later than 16 years ago (2005 included); a machine is considered old if it was introduced into the factory more than 16 years ago. Machine renovations that took place no more than six years ago (2015 included) are also taken into consideration. It is categorized as a level 3 soft constraint because it does not directly affect the possibility of machining a product, but it affects productivity, cost and quality outcomes.

- **Machine verification**
  It is an automatic system to check the health of the machine according to a standardized approach. This capability determines whether this verification system is in place or not. It is categorized as a level 3 soft constraint.

5.2.1 KMCs table

The KMCs table is presented in this section (Figure 5.1 and Figure 5.2). At this initial stage, the table only takes into consideration the data referring to general capabilities, e.g., structure, machining operation, process capability, etc. Data concerning specific capabilities (capabilities that relate to specific job types and indicated in the table with XX) is not compiled as it depends on specific operations and requires further analysis (Section 5.4.1).

The layout of the KMCs table presents the list of machines on the rows, categorized into machine types (turning, milling and multitask). The columns show the machine capabilities, organized into hard and soft constraints. The outcome of the table consists of only 1 and 0 values, where 1 indicates a positive response and 0 indicates a negative response to the machine capability. The choice of having only two values was dictated by the purpose of reducing complexity, avoiding compatibility problems that may arise while combining KMCs and KPFs, thus allowing easier compilation of data for the association matrices. Nevertheless, not all capabilities can be directly expressed with a binary approach (1 and 0). Some of them cannot be generalized without having first studied them in relation to the KPFs and their related job types. Therefore, for the machine capabilities that cannot be generalized, threshold values (indicated in the KMCs table with a not specified XX value) must be obtained (Section 5.4.1). After obtaining the threshold values for each operation, it is possible to compile the association matrices with a 1 if the machine capability meets the threshold value, or with a 0 if the machine capability does not meet the threshold value. The list of the machine capabilities that require threshold values is presented in Table 5.2 and is explained in detail below.

Table 5.2: KMCs that require threshold values

KMC	**KMC state**
Dimensionality	Maximum diameter Minimum Inside Diameter (ID) Height
Tool magazine size	Non-rotating tools Rotating tools
Axes of motion	-
Internal milling head	Speed Torque
External milling head	Speed Torque
Maximum tool length	-
Coolant	Internal coolant pressure
Rotary table max speed	-
Drilling spindle	Speed
Number of touch probes	-

- **Dimensionality**
  The machine's maximum diameter, minimum ID and height, which represent the requirements of the workpiece to fit into the machine, cannot be expressed directly with 1 or 0. Threshold values dependent on each specific operation (that is a set of a certain number of job types) need to be used. After setting a threshold value for all the dimensionality parameters, if the machine can accommodate the workpiece, the outcome of the table is 1, if not the outcome is 0. For this study, due to difficulties in retrieving data on the ID, this capability is left blank, but it is not excluded from the model as it can be used for future updates.

- **Tool magazine size**
  This machine capability is once again strictly dependent on each specific operation. Therefore, it is necessary to specify the threshold number (in this case the minimum number required) of tools that must be present in the tool magazine for each operation. If the machine has a number of tools contained in the tool magazine that satisfies the requirement for a given operation, the outcome of the table is 1, if not it is 0.

- **Axes of motion**
  Here the threshold is represented by the minimum number of axes of motion required to perform a given operation. If the machine has a number of axes at least equal to the threshold value, the result of the table is 1, otherwise it is 0. Full 5-axes machines automatically have 1 because they are able to perform all kinds of machining operations. The maximum number of axes of motion that a machine has is indicated in a separate column next to the machine name column.

- **Internal milling head (speed and torque)**
  The speed and torque are factors closely related to each other. For example, it is convenient in terms of productivity to machine at high speed, but some job types have tools that require higher torque. The speed and torque are strictly dependent on each specific operation. Therefore, a threshold value for both speed and torque must be set according to the specific operation. If the machine satisfies the threshold value, the outcome of the table is 1, if not it is 0. For this study, due to difficulties in retrieving torque data, this capability is left blank, but it is not excluded from the model since it can be used for future updates.

- **External milling head (speed and torque)**
  The same is true of the internal milling head.

- **Maximum tool length**
  A specific threshold value for the tool length must be set according to each specific operation. If the machine meets that threshold value, the outcome of the table is 1, if not it is 0.

- **Internal coolant pressure**
  It is a value that directly depends on each specific job type. Therefore, a threshold value (minimum pressure required) for the required coolant pressure must be set according to each specific operation. If the machine satisfies the threshold value, the outcome of the table is 1, if not it is 0.

- **Rotary table max speed**
  Even in this case, a specific threshold value must be set according to each specific operation. If the machine meets that threshold value, the outcome of the table is 1, if not it is 0.

- **Drilling spindle (speed)**
  The drilling spindle speed is taken into consideration by setting a minimum threshold value according to each specific operation. If the machine meets that threshold value, the outcome of the table is 1, if not it is 0.

- **Number of touch probes**
  Since the number of touch probes required depends on the number and type of product features that need to be probed during the same operation, the suitable number of touch probes must be set according to each specific operation. If the machine satisfies this number, the outcome of the table is 1, if not it is 0.

The KMCs table is shown in Figure 5.1 and Figure 5.2. The cells highlighted in light yellow indicate missing data and the cells highlighted in light orange indicate data retrieved through an “inheriting” process detailed in Section 5.6.

Machine type	Machine name	Maximum number of axes of motion	Machine capabilities																								
			Hard constraints											Soft constraints													
														Level 1	Level 1	Level 1					Level 1						
			Structure		Dimensionality		Machining operation			Tool magazine size		Mass		Axes of motion	Dimensionality	Internal milling head					External milling head						
			Vertical	Horizontal	Max diameter [mm]	Height [mm]	Non-rotating	Rotating		Non-rotating tools	Rotating tools	Lightweight	Heavyweight	≥ XX	Min inside diameter (ID) [mm]	Automatic tool change present	Speed [rpm]	Torque [Nm]	Under tilt	Tool measurement (laser) present	Present	Programmable head present	Automatic tool change present	Speed [rpm]	Torque [Nm]	Under tilt	Automated tool measurement (laser) present
					≥ XX	≥ XX	Turning	Milling	Drilling	≥ XX	≥ XX				≤ XX		≥ XX	XX	≤ -5 degrees					≥ XX	XX	≤ -5 degrees	
Turning	Machine T1		1	0			1	0	1												1	1	1				1
	Machine T2		1	0			1	0	1												1	1	1				1
	Machine T3		1	0			1	0	1												1	0	1				
	Machine T4		1	0			1	0	1												1	0	1				
	Machine T5		1	0			1	0	1												1	0	1				1
	Machine T6		1	0			1	0	1												1	1	1				1
	Machine T7		1	0			1	0	1												1	1	1				1
	Machine T8		1	0			1	0	1												1	1	1				1
	Machine T9		1	0			1	0	1												1	0	1				
	Machine T10		1	0			1	0	1												0						
	Machine T11		1	0			1	0	1												0						
	Machine T12	5	1	0			1	0	1												0	0	0				0
	Machine T13	5	1	0			1	0	1												0	0	0				0
	Machine T14	5	1	0			1	0	1												0	0	0				0
	Machine T15	5	1	0			1	0	1												0	0	0				0
	Machine T16	5	1	0			1	0	1												0	0	0				0
	Machine T17	1 + 1	1	0			1	0	0												0	0	0				0
Milling	Machine M1	5	1	0			0	1	1												0	0	0				0
	Machine M2	5	1	0			0	1	1												1	0	0				0
	Machine M3	5	1	0			0	1	1												0	0	0				0
	Machine M4	5	1	0			0	1	1												0	0	0				0
	Machine M5	5	1	0			0	1	1												0	0	0				0
	Machine M6	5	1	0			0	1	1												0	0	0				0
	Machine M7	5	1	0			0	1	1												0	0	0				0
	Machine M8	5	1	0			0	1	1												0	0	0				0
	Machine M9	4 + 1	1	0			0	1	1												1	1	1				1
	Machine M10	4 + 1	1	0			0	1	1												1	1	1				1
	Machine M11	5	1	0			0	1	1												1	1	1				1
Multitask	Machine TM1	5	1	0			1	1	1												1	1	1				1
	Machine TM2	5	1	0			1	1	1												1	1	0				0
	Machine TM3	5	1	0			1	1	1												0	0	0				0
	Machine TM4	5	1	0			1	1	1												0	0	0				0
	Machine TM5	5	1	0			1	1	1												1	1	0				0
	Machine TM6	5	1	0			1	1	1												0	0	0				0
	Machine TM7	5	1	0			1	1	1												0	0	0				0
	Machine TM8	5	1	0			1	1	1												0	0	0				0
	Machine TM9	5	1	0			1	1	1												1	1	0				0
	Machine TM10	5	1	0			1	1	1												1	1	0				0
	Machine TM11	5	1	0			1	1	1												0	0	0				0

Figure 5.1: The KMCs table (part 1)

Machine type	Machine name	Maximum number of axes of motion	Machine capabilities																			
			Soft constraints																			
			Level 1	Level 2			Level 2	Level 2		Level 2	Level 2		Level 2	Level 2	Level 2		Level 3			Level 3		Level 3
			Maximum tool length [mm]	Coolant			Process capability	Tool measurement present		Rotary table max speed	Drilling spindle		Number of touch probes	Number of pallets	Environmental factors		Control system CNC generation			Machine age		Machine verification present
			≥ XX	Internal coolant pressure [bar]	Internal coolant mid-jet	Internal coolant high-jet	Cp ≥ 1.33	Turning (contact probes)	Milling (laser)	≥ XX	Speed	Tool measurement (laser) present	≥ XX	≥ 1	Noise generation	Coolant hazard	New	Medium	Old	Bought after 2005 (included)	Renovated after 2015 (included)	
				≥ XX							≥ XX											
Turning	Machine T1	▨	▨		▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	0	0	▨
	Machine T2	▨	▨		▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	1	1	▨
	Machine T3	▨	▨		▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	0	1	▨
	Machine T4	▨	▨		▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	0	1	▨
	Machine T5	▨	▨		▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	▨	1	▨
	Machine T6	▨	▨		▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	1	0	▨
	Machine T7	▨	▨		▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	1	0	▨
	Machine T8	▨	▨		▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	1	0	▨
	Machine T9	▨	▨		▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	0	1	▨
	Machine T10	▨	▨	▨	▨	▨	▨	1	▨		▨	0			▨	▨	▨	▨	▨	0	0	▨
	Machine T11	▨	▨		▨	▨	▨	1	▨	▨	▨	1	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Machine T12	5	▨		▨	▨	▨	1	▨			1		▨	▨	▨	▨	▨	▨	0	1	▨
	Machine T13	5			▨	▨	▨	1	▨			1		▨	▨	▨	▨	▨	▨	0	1	▨
	Machine T14	5	▨		▨	▨	▨	1	▨			1		▨	▨	▨	▨	▨	▨	0	0	▨
	Machine T15	5	▨		▨	▨	▨	1	▨			1		▨	▨	▨	▨	▨	▨	0	0	▨
	Machine T16	5			▨	▨	▨	1	▨			1		▨	▨	▨	▨	▨	▨	0	1	▨
	Machine T17	1 + 1	▨		▨	▨	▨	1	▨	▨	▨	0			▨	▨	▨	▨	▨	1	0	▨
Milling	Machine M1	5	▨		▨	▨	▨	0	▨			0			▨	▨	▨	▨	▨	0	0	▨
	Machine M2	5			▨	▨	▨	0	▨			1			▨	▨	▨	▨	▨	1	0	▨
	Machine M3	5	▨		▨	▨	▨	0	▨			1			▨	▨	▨	▨	▨	1	0	▨
	Machine M4	5	▨		▨	▨	▨	0	▨			1			▨	▨	▨	▨	▨	0	▨	▨
	Machine M5	5			▨	▨	▨	0	▨			1			▨	▨	▨	▨	▨	0	▨	▨
	Machine M6	5			▨	▨	▨	0	▨			1			▨	▨	▨	▨	▨	0	▨	▨
	Machine M7	5			▨	▨	▨	0	▨			1			▨	▨	▨	▨	▨	0	▨	▨
	Machine M8	5			▨	▨	▨	0	▨			0			▨	▨	▨	▨	▨	0	0	▨
	Machine M9	4 + 1			▨	▨	▨	0	▨			1			▨	▨	▨	▨	▨	0	0	▨
	Machine M10	4 + 1			▨	▨	▨	0	▨			1			▨	▨	▨	▨	▨	0	0	▨
	Machine M11	5			▨	▨	▨	0	▨			1			▨	▨	▨	▨	▨	0	0	▨
Multitask	Machine TM1	5			▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	1	0	▨
	Machine TM2	5			▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	1	0	▨
	Machine TM3	5			▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	1	0	▨
	Machine TM4	5			▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	1	0	▨
	Machine TM5	5			▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	1	0	▨
	Machine TM6	5		▨	▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	0	0	▨
	Machine TM7	5		▨	▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	0	▨	▨
	Machine TM8	5			▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	1	0	▨
	Machine TM9	5			▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	1	0	▨
	Machine TM10	5			▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	1	0	▨
	Machine TM11	5			▨	▨	▨	1	▨			1			▨	▨	▨	▨	▨	1	0	▨

Figure 5.2: The KMCs table (part 2)

5.3 Key Product Features (KPFs)

In this section, the Key Product Features (KPFs) of the three products of interest (TEC, LPT and ICC) are identified. A specific model (with specific dimensions, design and technical features) of each of the three products was assessed. However, in compliance with the non-disclosure agreement, the actual names of the three product models are not included in the final report. Their generic names are kept instead. Detailed images of such products cannot be included either, as they contain sensitive data and confidential information.

5.3.1 TEC

The KPFs of interest for the TEC are:

- **Flanges**
  Bolted flanges are important assembly elements to connect parts when welding is not an option, e.g., when it is needed to easily disassemble the parts, change them when worn, inspect them, etc. They ensure perfect alignment of the parts connected, preventing their relative movement, or worse their separation during normal functioning. Flanges may be scalloped to obtain weight reduction and better resistance to thermal stresses. The TEC presents flanges to connect the LPT case, the bearing housing system, the primary nozzle and the plug. They are listed below:
  - The forward outer flange (LPT-flange) connects the outer case of the TEC to the LPT case (Figure 5.3).
  - The rear outer flange (T-outer flange) connects the outer case of the TEC to the primary nozzle (Figure 5.3).
  - The rear inner flange connects the inner case of the TEC to the plug (Figure 5.3).
  - The bearing house flange connects the TEC to the bearing house (through a support cone welded to the hub) (Figure 5.3).
- **Rear engine mounts**
  They are structural features located at the top of the TEC, designed to ensure that the engine is correctly fixed to the airplane body. They are commonly three in number, where the middle one is used as a fail-safe system (Figure 5.3). High tolerances are required for a correct and precise pairing between the TEC structure and the airplane body. For this reason, bushings are included in the mounts to ensure high tolerances and predict wear between the holes and the pin.
- **Bosses**
  They can be of three types:
  - Ground handling bosses are located on the outer case of the TEC and serve to transport or handle the structure on the ground when it needs to be maintained or repaired. The main reason to have ground handling bosses is that it is not recommended to lift the TEC from the rear engine mounts, due to their strict compliance to high tolerances. Handling the TEC from the rear engine mounts would expose them to damages and

    eventually coupling problems between the TEC structure and the airplane body.
  - Tube support bosses are located on the outer case of the TEC and serve to support the tubes located inside the struts (Figure 5.3).
  - Datum bosses are used to provide datum planes when fixing the parts before performing machining operations.

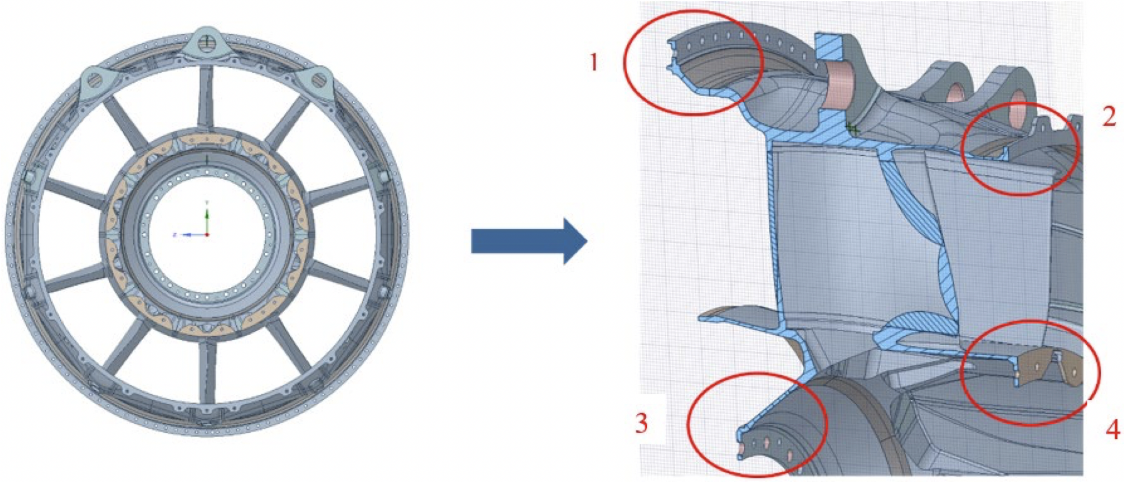


Figure 5.3: Two views of the TEC showing the three engine mounts and the tube support bosses on the left, and the forward outer flange (1), rear outer flange (2), bearing house flange (3) and rear inner flange (4) on the right (Bonifaz, 2019)

5.3.2 LPT case

The KPFs of interest for the LPT case are:

- **Flanges**
  The LPT case presents the following flanges:
  - The TEC flange connects the LPT case to the TEC (Figure 5.4).
  - The HPT flange connects the LPT case to the HPT structure (Figure 5.4).
- **Tunnel hooks**
  They are internal features to keep the static vanes in place (Figure 5.4).
- **Deflectors**
  They are specific features shaped into the inner profile of the LPT case, on the TEC side.
- **Bosses**
  They are located on the lateral surface.
- **Holes**
  They are located on the lateral surface for various functions, such as to allow for lubrication.

Figure 5.4: The TEC flange in the foreground and the HPT flange in the background. The tunnel hooks are also visible in the inner profile of the barrel (Runnemalm & Alberg, 2007)

5.3.3 ICC

The KPFs of interest for the ICC are:

- **Flanges**
  The ICC presents the following flanges:
  - The front flange connects the ICC to the LPC (Figure 5.5).
  - Outer annulus IP flange.
  - The hub flange is located on the largest diameter of the hub.
  - Firewall flange (Figure 5.5).
  - The CC flange connects the ICC to the intermediate-pressure compressor (Figure 5.5).
  - HPC outer flange.
  - HPC inner flange.
- **Bosses**
  They can be of several types depending on their purpose and location:
  - Anti-ice boss on the front case sheet (Figure 5.5).
  - Handling bleed bosses on the front case sheet (Figure 5.5).
  - Firewall bosses on the flat surface of the firewall.
  - Cabin panel bosses on the cabin panel.
- **Engine mounts** (Figure 5.5)
- **Thrust lugs** (Figure 5.5)
- **Cabin bleed**

Figure 5.5: Some of the visible components of the ICC (Peña, 2015)

5.4 Operations list

In this section, the job types performed on each KPF are identified. Specifically, each operation consists of one or more job types performed on one or several KPFs. The same operation names used by GKN Aerospace have been adopted in this section. Due to the sensitivity of the data, images showing specific KPFs could not be included in this report.

- **TEC**
  The machining operations of interest for the TEC concern two operations (Table 5.3):
  - **Operation 1600**
    It is performed on the side of the TEC that is connected to the LPT case. The job types on this side of the TEC are performed by a turning machine with an external drilling head. The first step involves the turning of the forward outer flange and the bearing house flange. The second step concerns the drilling of the holes of the flanges. Having a machine with an internal milling head, such as a multitask, may be another possibility for drilling the holes of the flanges instead of using a turning machine with an external milling head. As the holes do not lay on inclined surfaces (their axes are parallel to the TEC axis), the external milling head does not need to be programmable.
  - **Operation 1700**
    It is performed on the side of the TEC that is connected to the primary nozzle. The machining operations on this side are performed by a multitask machine. However, they may also be performed on a 5-axes milling machine. The first step concerns the milling of the rear outer flange and rear inner flange. The process is mainly about milling the scallops, even if some surfaces can also be turned. The second step involves the drilling of the holes of the rear outer and rear inner flanges. The bosses are machined with the machine's internal milling head, utilizing the machine's five axis capability in a 3 + 2 axes operation, as they are neither parallel nor perpendicular to the TEC axis. In the case the bosses are either vertical or horizontal, they can be machined with a 4-axes machine, instead of a 5-axes one.

Table 5.3: TEC operations

Operation	**KPF**
1600	Forward outer flange Bearing house flange
1700	Rear outer flange Rear inner flange Rear engine mounts Ground handling bosses Tube support bosses Datum bosses

- **LPT case**
  The machining operations investigated on the LPT case (Table 5.4) are:
  - **Operation 500**
    It is performed on the side of the LPT case that is connected to the HPT. This operation is performed on a turning machine with the presence of an external milling head. The first step involves the turning of the HPT flange. The second step concerns the scalloping and drilling of the holes of the HPT flange.
  - **Operation 600**
    It is performed on the side of the LPT case connected to the TEC. This operation is performed on a turning machine with the presence of an external milling head. The TEC flange is first turned, then milled to shape it and finally drilled to make the holes. In this operation, turning is also used to shape the tunnel hooks into the inner surface of the LPT case.
  - **Operation 700**
    It is performed on the internal surface of the LPT case to machine the deflectors. This operation is performed on a milling machine without the need of turning capability.
  - **Operation 800**
    It is performed on the external wall of the LPT case to make holes and bosses. This operation is performed on a milling machine without the need of turning capability. To drill the holes that lay in directions other than horizontal or vertical (with respect to the LPT case axis), a 3 + 2 axes capability is required.

Table 5.4: LPT case operations

Operation	**KPF**
500	HPT flange
600	TEC flange Tunnel hooks
700	Deflectors
800	Bosses Holes

- **ICC**
  The machining operations of interest for the ICC (Table 5.5) are:
  - **Operation 4100**
    This operation is performed on a turning machine with the presence of external milling heads. The three flanges included in this operation, i.e., the front flange, the outer annulus IP flange and the hub flange, are first turned. The holes on the front flange are drilled with a drilling head. However, the outer annulus IP flange and the hub flange require more complex machining operations than just drilling. The anti-ice boss and the handling bleed bosses need to be machined with an external milling head. Therefore, the adoption of an external milling head for this operation is recommended.
  - **Operation 4200**
    This operation is performed on a turning machine equipped with external milling heads. The three flanges included in this operation, i.e., the CC flange, the HPC outer flange and the HPC inner flange, are first turned. Thereafter, they are milled to shape the scallops. Lastly, the holes on all three flanges are drilled.
  - **Operation 4300**
    This operation involves the machining of the firewall flange and engine mounts. The related job types are performed on a milling machine (portal milling machine) without the need of turning capability. The holes on the flange are machined either with milling or drilling tools.
  - **Operation 4400**
    This set of job types is performed on a milling machine (portal milling machine) without the need of turning capability. The product features to be machined in operation 4400 are: the bosses on the flat surface of the firewall (firewall bosses), the bosses on the cabin panel (cabin panel bosses), thrust lugs and the cabin bleed.

Table 5.5: ICC operations

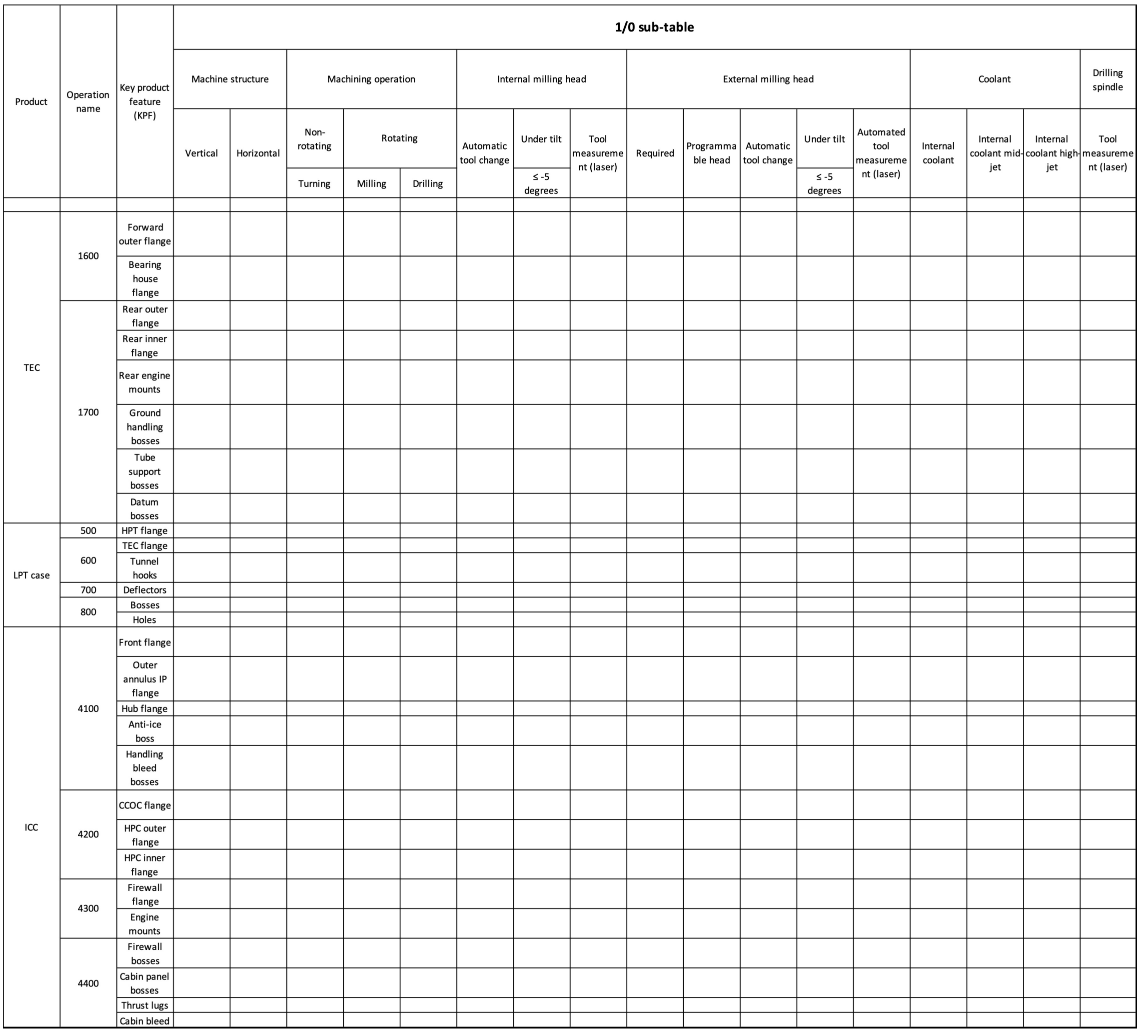
Operation	KPF
4100	Front flange Outer annulus IP flange Hub flange Anti-ice boss Handling bleed bosses
4200	CC flange HPC outer flange HPC inner flange
4300	Firewall flange Engine mounts
4400	Firewall bosses Cabin panel bosses Thrust lugs Cabin bleed

5.4.1 Operations table

The operations table contains the parameters relating to the KPFs and the machining operations performed on them. Its layout presents the products on the rows, further subdivided into KPFs along with the specific operation. The columns show all the parameters that need to be matched with the KMCs. For a more rigorous and accurate coupling between the product and machine dimensions, the parameters shown in the operations table were chosen to be the same as the ones in the KMCs table, but they are considered from the product's perspective. The main difference between the operations table and the KMCs table is that the former is divided into two sub-tables, of which the first, called threshold sub-table, does not adopt a binary approach (1 and 0). The reason is that some parameters are strictly related to each specific KPF (and to the related job type) and can only be expressed in terms of specific values (numbers other than 1 or 0). Then, a threshold value for each operation (comprising multiple job types to machine several KPFs) is identified and used to compile the association matrices. The other sub-table, called 1/0 table, presents the same binary approach as the KMCs table, so it consists of only 1 and 0 values, where 1 indicates a positive response and 0 a negative response. The threshold sub-table is shown in Figure 5.6 and the 1/0 sub-table is shown in Figure 5.7.

Product	Operation name	Key product feature (KPF)	Threshold sub-table														
			Dimentionality			Tool magazine size			Number of axes of motion	Internal milling head		External milling head		Internal coolant pressure [bar]	Tool length [mm]	Rotary table max speed [rpm]	Drilling spindle speed [rpm]
			Max part diameter [mm]	Min inside diameter (ID) [mm]	Max height [mm]	Number of non-rotating tools	Number of rotating tools	Number of touch probes		Speed [rpm]	Torque [Nm]	Speed [rpm]	Torque [Nm]				
TEC	1600	Forward outer flange															
		Bearing house flange															
	1700	Rear outer flange															
		Rear inner flange															
		Rear engine mounts															
		Ground handling bosses															
		Tube support bosses															
		Datum bosses															
LPT case	500	HPT flange															
	600	TEC flange															
		Tunnel hooks															
	700	Deflectors															
	800	Bosses															
		Holes															
ICC	4100	Front flange															
		Outer annulus IP flange															
		Hub flange															
		Anti-ice boss															
		Handling bleed bosses															
	4200	CCOC flange															
		HPC outer flange															
		HPC inner flange															
	4300	Firewall flange															
		Engine mounts															
	4400	Firewall bosses															
		Cabin panel bosses															
		Thrust lugs															
		Cabin bleed															
Threshold values TEC	1600																
	1700																
Threshold values LPT case	500																
	600																
	700																
	800																
Threshold values ICC	4100																
	4200																
	4300																
	4400																

Figure 5.6: The threshold sub-table



Product	Operation name	Key product feature (KPF)	1/0 sub-table																	
			Machine structure		Machining operation				Internal milling head			External milling head					Coolant			Drilling spindle
			Vertical	Horizontal	Non-rotating	Rotating			Automatic tool change	Under tilt	Tool measurement (laser)	Required	Programmable head	Automatic tool change	Under tilt	Automated tool measurement (laser)	Internal coolant	Internal coolant mid-jet	Internal coolant high-jet	Tool measurement (laser)
						Turning	Milling	Drilling		≤ -5 degrees					≤ -5 degrees					
TEC	1600	Forward outer flange																		
		Bearing house flange																		
	1700	Rear outer flange																		
		Rear inner flange																		
		Rear engine mounts																		
		Ground handling bosses																		
		Tube support bosses																		
		Datum bosses																		
LPT case	500	HPT flange																		
	600	TEC flange																		
		Tunnel hooks																		
	700	Deflectors																		
	800	Bosses																		
		Holes																		
ICC	4100	Front flange																		
		Outer annulus IP flange																		
		Hub flange																		
		Anti-ice boss																		
		Handling bleed bosses																		
	4200	CCOC flange																		
		HPC outer flange																		
		HPC inner flange																		
	4300	Firewall flange																		
		Engine mounts																		
	4400	Firewall bosses																		
		Cabin panel bosses																		
		Thrust lugs																		
		Cabin bleed																		

Figure 5.7: The 1/0 sub-table

The list of the parameters comprised into the operations table, divided into the two sub-tables, is presented below:

- **Threshold sub-table**
    - **Dimensionality**
      The maximum diameter, the minimum Inside Diameter (ID) and the maximum height of each KPF are specified as values expressed in millimeters. As already specified in Section 5.2.1, the ID is not considered for this study, but it is not excluded as it can be used for future model updates.

    - **Tool magazine size**
      This parameter specifies the minimum number of both non-rotating and rotating tools required to perform a specific job type on a given KPF. The minimum number of touch probes required to probe each KPF is also part of the tool magazine.

    - **Number of axes of motion**
      It is the minimum number of axes of motion required to perform a specific job type on a given KPF.

    - **Internal milling head (speed and torque)**
      The speed and torque values required to perform a specific job type are specific to each KPF. The speed is expressed as a threshold value in rpm and the torque is expressed as a threshold value in Nm. As already specified in Section 5.2.1, the torque is not considered for this study, but it is not excluded as it can be used for future model updates.

    - **External milling head (speed and torque)**
      The same is true of the internal milling head.

    - **Internal coolant pressure**
      It describes the coolant pressure that is required to perform a specific job type on a given KPF. It is expressed in bar.

    - **Maximum tool length**
      A specific threshold value, which indicates the minimum required tool length, is identified for each KPF. The value is expressed in terms of millimeters.

    - **Rotary table max speed**
      The maximum speed of the rotary table required to machine each KPF is specified with a threshold value expressed in rpm.

    - **Drilling spindle speed**
      The minimum speed required for drilling operations performed on each KPF is specified with a threshold value expressed in rpm.

- **1/0 sub-table**
    - **Machine structure**
      It is the structure, either vertical or horizontal, that the machine is required to have in order to machine a given KPF.

    - **Machining operation**
      It represents the principal machining operation(s) required to machine a given KPF. It can be non-rotating (turning) or rotating (milling and drilling).

    - **Internal milling head**
      It determines if some additional milling features, such as automatic tool change, under tilt and tool measurements, are required to machine a given KPF.

    - **External milling head**
      This parameter shows if the external milling head is required to perform a certain job type on a given KPF. A programmable external milling head is recommended when performing machining operations with directions other than horizontal or vertical.

    - **Coolant**
      It takes into consideration the coolant type in terms of pressure required to machine a given KPF.

    - **Drilling spindle**
      It represents the requirement of a tool measurement system (laser) for the drilling spindle to machine a given KPF.

5.5 Association of KMCs and KPFs

This section describes the association process of the machine capabilities and product features dimensions. This is achieved by means of a matrix consisting of three dimensions, i.e., the operation of interest (e.g., 1600, 500, etc.), the technical parameters required to perform the job types included in that operation and the machines available to perform the job types included in that operation. The association matrix is based on the KMCs table, but with some modifications that make it specific for each given operation. Therefore, the approach results in as many association matrices as the number of operations of interest.

The combination of the two main dimensions of this study follows a precise step-by-step procedure. To obtain associations between the KMCs and KPFs, each operation is accessed individually, in order to capture as much detail as possible. For instance, since in this study two operations (1600 and 1700) are considered for the TEC, the findings for the TEC result in two different matrices, one for each operation. Then, if a single matrix showing resource allocations for the whole product (for example for both operations 1600 and 1700 for the TEC) needs to be identified, a further step must be carried out (Section 5.7). In this step, the individual results obtained for each operation are merged to create one association matrix that identifies resource allocations to manufacture the whole product. An additional level of detail, further investigated in Section 5.8, allows to find optimal resource allocation for a set of products, not only one.

The basic procedure of the approach reflects the following structure:

1. Starting from the operations table, the requirements for each KPF are specified.
    (a) The threshold sub-table is filled in with numbers other than 1 or 0. In the threshold sub-table, a value is specified for each job type performed on each KPF. Thereafter, at the bottom of the threshold sub-table (in the separate table present at the bottom of Figure 5.6), one threshold value for each parameter (e.g., max diameter, internal coolant pressure, tool length, etc.) and for each operation (including one or several job types) is determined. To describe how the threshold sub-table works in practice, operation 600 of the LPT case is taken as an example. Operation 600 includes two job types, i.e., the machining operations performed on the TEC flange and the machining operations performed on the tunnel hooks. The tool magazine size required for the non-rotating tools is 12 tools for the TEC flange and 16 tools for the tunnel hooks. Therefore, the threshold value for the tool magazine size (non-rotating tools) required to perform the entire operation 600 is 16. The same applies for the required axes of motion. Three axes of motion are required to machine the TEC flange and just two axes of motion for the tunnel hooks, hence the minimum required number of axes of motion (threshold value) to perform the entire operation 600 is three. These values are noted at the bottom of the threshold sub-table in the separate table at the bottom of Figure 5.6. This process is similarly carried out for all the parameters (e.g., max diameter, internal coolant pressure, tool length, etc.) of the threshold sub-table and it is referred to each operation.
    (b) The 1/0 sub-table is filled in with either 1 (positive response) or 0 (negative response). To describe how the 1/0 sub-table works in practice, operation 600 is taken up again as an example. Both the TEC flange and tunnel hooks require a machine with a vertical structure to be machined. Therefore, the machine structure parameter indicates this requirement by displaying a 1 to the vertical structure cell, and a 0 to the horizontal structure cell. The same mechanism applies to the other parameters of the 1/0 sub-table.
2. The threshold values of each operation determined in step 1.a are substituted in place of XX in the association matrix (Figure 5.1 and Figure 5.2), which is specific to each operation. This association matrix is based on the KMCs table (in fact it is a duplicate of the KMCs table that borrows the same structure from it). The resulting association matrices show the relationship between operations and machines for a specific operation. Taking up the example of

operation 600, the two threshold values determined in step 1.a (16 non-rotating tools in the tool magazine and three axes of motion required for operation 600) are substituted in the place of the XX of the non-rotating tools and axes of motion columns respectively of the association matrix for operation 600. Similarly, the other threshold values of operation 600 (e.g., max diameter, internal coolant pressure, tool length, etc.) are substituted in their respective columns in the association matrix.

3. Both values from steps 1.a and 1.b are validated with respect to the data of the machines that is present in a database directly retrieved from GKN Aerospace. This database cannot be disclosed due to the sensitivity of the information. After validating the data from the operations table with the GKN Aerospace database, the machines can be qualified for performing that particular operation. Taking up the example of operation 600 again, the threshold values concerning the tool magazine size (16 non-rotating tools) and the three axes of motion from point 1.a and the 1/0 value concerning the machine structure (vertical) from point 1.b are validated with the data of the machines present in the GKN Aerospace database. The same procedure is followed for all the threshold values contained in the threshold sub-table and for all the parameters contained in the 1/0 sub-table. After validating this data, the machines that fulfill the requirements for operation 600 are qualified.

The qualification procedure works according to three main levels:

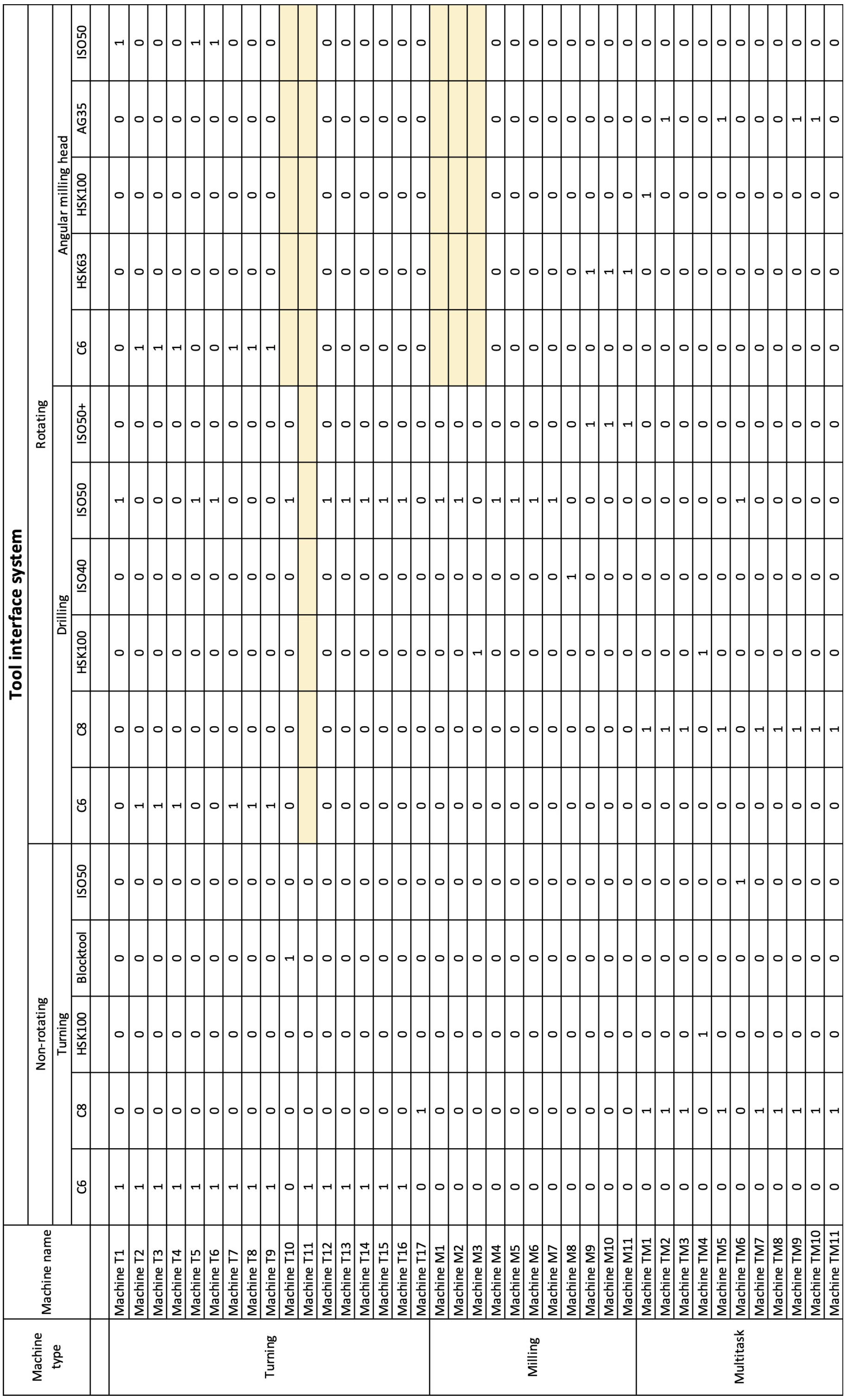
1. The first level of qualification concerns the hard constraints shown in Section 5.2. In order to qualify a machine, these requirements must compulsorily be met to perform a certain operation on a given KPF or on multiple KPFs.
2. The second level of qualification concerns the soft constraints shown in Section 5.2. Soft constraints are divided into three levels, depending on their effect on machine qualification. Level 1 soft constraint lies between the first and second level of qualification, as it is a watershed between hard and soft constraints. If the soft constraints are not met, it is still possible to perform the given operation, but presumably with reduced quality and higher costs. Therefore, soft constraints (mainly level 2 and 3) would be preferable to be met, but they are not a must to qualify the machine.
3. The third level of qualification is a further level of detail that analyzes additional properties, which could not be included into the KMCs and operations table due to incompatibilities with the binary approach. They are kept separate and discussed in more detail in the next section (Section 5.5.1).

5.5.1 Additional level of qualification

This further level of qualification adds other technical parameters to the approach. The properties considered are the following:

- **Tool interface system**
  This property indicates the tool interface system that each machine uses. It is divided according to the machining operations of interest, i.e., non-rotating (turning) and rotating (milling and drilling). In general, the tool interface sys-

tem affects the tool change because some tools are suitable just for a specific interface system, and not for another. Figure 5.8 shows the different tool interface systems for each machine. The cells highlighted in light yellow indicate missing data.



Machine type	Machine name	Tool interface system																
		Non-rotating					Rotating											
		Turning					Drilling						Angular milling head					
		C6	C8	HSK100	Blocktool	ISO50	C6	C8	HSK100	ISO40	ISO50	ISO50+	C6	HSK63	HSK100	AG35	ISO50
Turning	Machine T1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
	Machine T2	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
	Machine T3	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
	Machine T4	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
	Machine T5	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
	Machine T6	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
	Machine T7	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
	Machine T8	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
	Machine T9	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
	Machine T10	0	0	0	1	0	0	0	0	0	1	0					
	Machine T11	1	0	0	0	0											
	Machine T12	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	Machine T13	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	Machine T14	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	Machine T15	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	Machine T16	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	Machine T17	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Milling	Machine M1	0	0	0	0	0	0	0	0	0	1	0					
	Machine M2	0	0	0	0	0	0	0	0	0	1	0					
	Machine M3	0	0	0	0	0	0	0	1	0	0	0					
	Machine M4	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	Machine M5	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	Machine M6	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	Machine M7	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	Machine M8	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	Machine M9	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
	Machine M10	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
	Machine M11	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
Multitask	Machine TM1	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0
	Machine TM2	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0
	Machine TM3	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	Machine TM4	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
	Machine TM5	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0
	Machine TM6	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
	Machine TM7	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	Machine TM8	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	Machine TM9	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0
	Machine TM10	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0
	Machine TM11	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0

Figure 5.8: Tool interface system

- **Machine operator skills**
  This capability includes all the key skills of machine operators. It is not a capability of the machine itself, but it directly influences the result of the machining operation. For instance, this property may include professional courses on how to machine special alloys e.g., titanium- and nickel-based alloys.

- **Rotation axes layout**
  The arrangement of the rotation axes (e.g., A- and B- axes) of the machines can affect their under tilt capability, as described in Section 5.2. In the case of one specific multitask machine at GKN Aerospace, problems arise when moving an operation from an A-axis to a B-axis machine. If an operation needs to be moved, it is much easier to move it from an existing A-axis machine to a new A-axis machine. Nevertheless, it is also possible to move it to a B-axis machine, but the qualification cost increases because reprogramming is required. Specifically, the final cost depends on the age of the controller, on their differences, and other technical factors. It is worth mentioning that the machine stability must also be taken into account when evaluating the arrangement of the rotation axes. Stability during milling operations may vary between different axis layouts, e.g., B-axis machines sometimes perform more stably than A-axis machines.

5.6 Examples of how the approach works in practice

This section shows how the developed approach is used in practice. The model was tested with only two out of three products, due to missing data for the ICC product. To run the model with the two chosen products (TEC and LPT case), a considerable amount of data on all their KPFs was required. Consequently, due to this complex and sometimes hindered data gathering process, it was not possible to collect some data, which are indicated in the table with empty cells highlighted in light yellow. Moreover, for some job types it was not possible to collect specific data (for each job type), but this data was provided by the GKN Aerospace representatives as general information for the entire operation. The KPFs data on the TEC was retrieved by the GKN Aerospace supervisor, and their current allocations were communicated by the manufacturing engineer manager. Both the KPFs data and the current allocations on the LPT case were retrieved by the CAM engineer. The current allocations are used in Chapter 6 to compare the results obtained through the model with the resource allocations that GKN Aerospace is currently adopting.

Another approach used to fill the gap of missing data concerned the “inheriting” of some information from the current allocations. The basic procedure of this process was the following:

1. Look at the current allocations for a given product, identifying the machines that are currently used to machine that product.
2. Derive the parameters needed (information that could not be retrieved in a

direct way) from the machine specifications, i.e., the KMCs.
3. Use the parameters retrieved in step 2 (threshold values, etc.) to compile the association matrices.

The same procedure can also be used to “inherit” information on the KMCs from machines that share similar characteristics. The data inherited with this procedure are highlighted in light orange in the KMCs table.

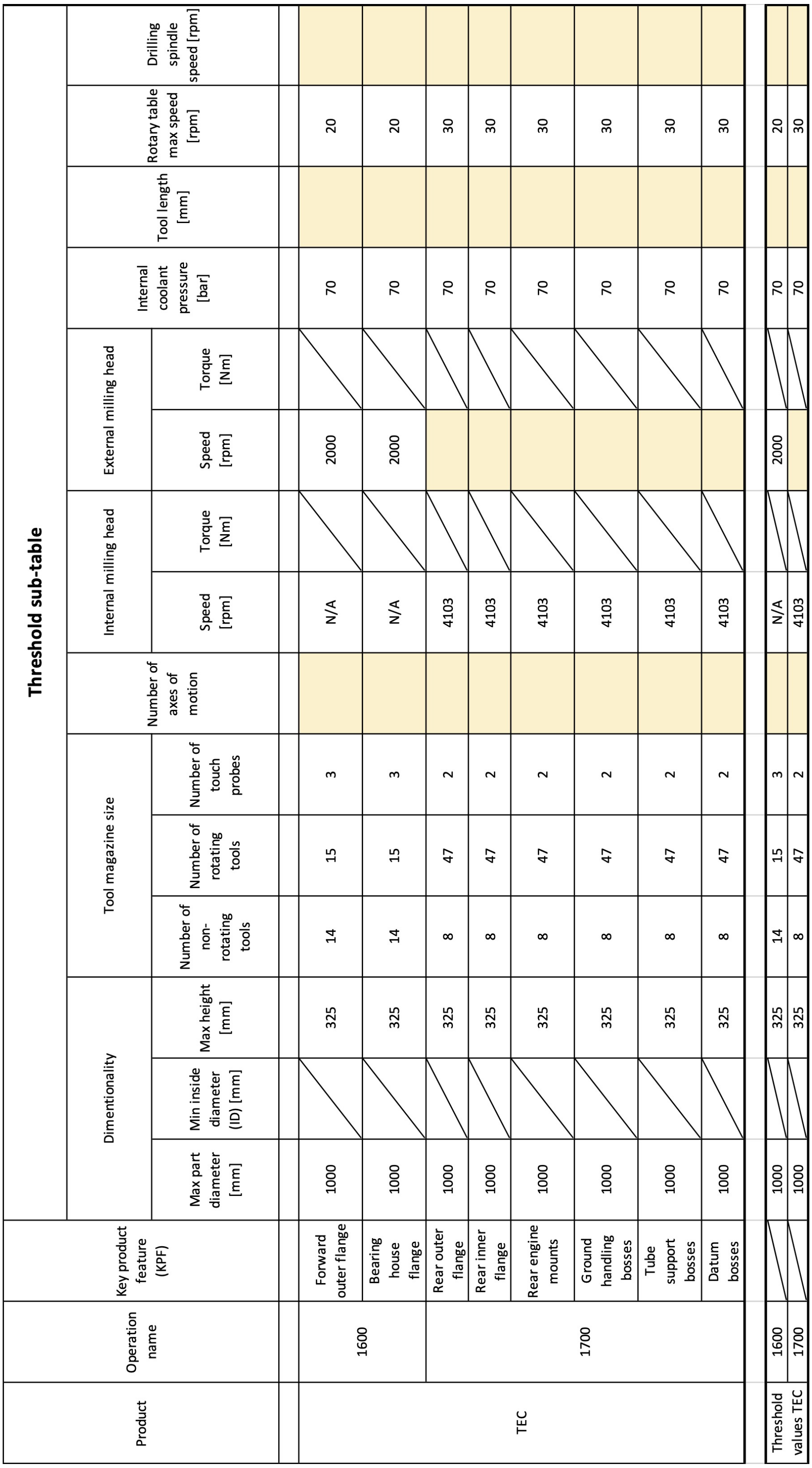
It is also important to mention that, despite the large amount of missing data, it was still ensured that the model worked at least with the hard constraints and some of the soft constraints (the ones that have been made available by the company representatives), so that the model would produce plausible results.

5.6.1 TEC

The process described in Section 5.5 was executed for operations 1600 and 1700 of the TEC. Figure 5.9 and Figure 5.10 show the threshold sub-table and the 1/0 sub-table respectively. The outcome of the threshold sub-table is the threshold values determined for both operations 1600 and 1700 and displayed in the small table at the bottom of the threshold sub-table (Figure 5.9). These threshold values are substituted in place of XX in the KMCs table, determining an association matrix for each of the two operations. The hard and soft constraints used to run the model for the TEC are shown in Table 5.6. Figures 5.11 and 5.12 and Figures 5.13 and 5.14 show the results of the process, revealing the machines selected for operations 1600 and 1700 respectively.

Table 5.6: The hard and soft constraints used to run the model for the TEC

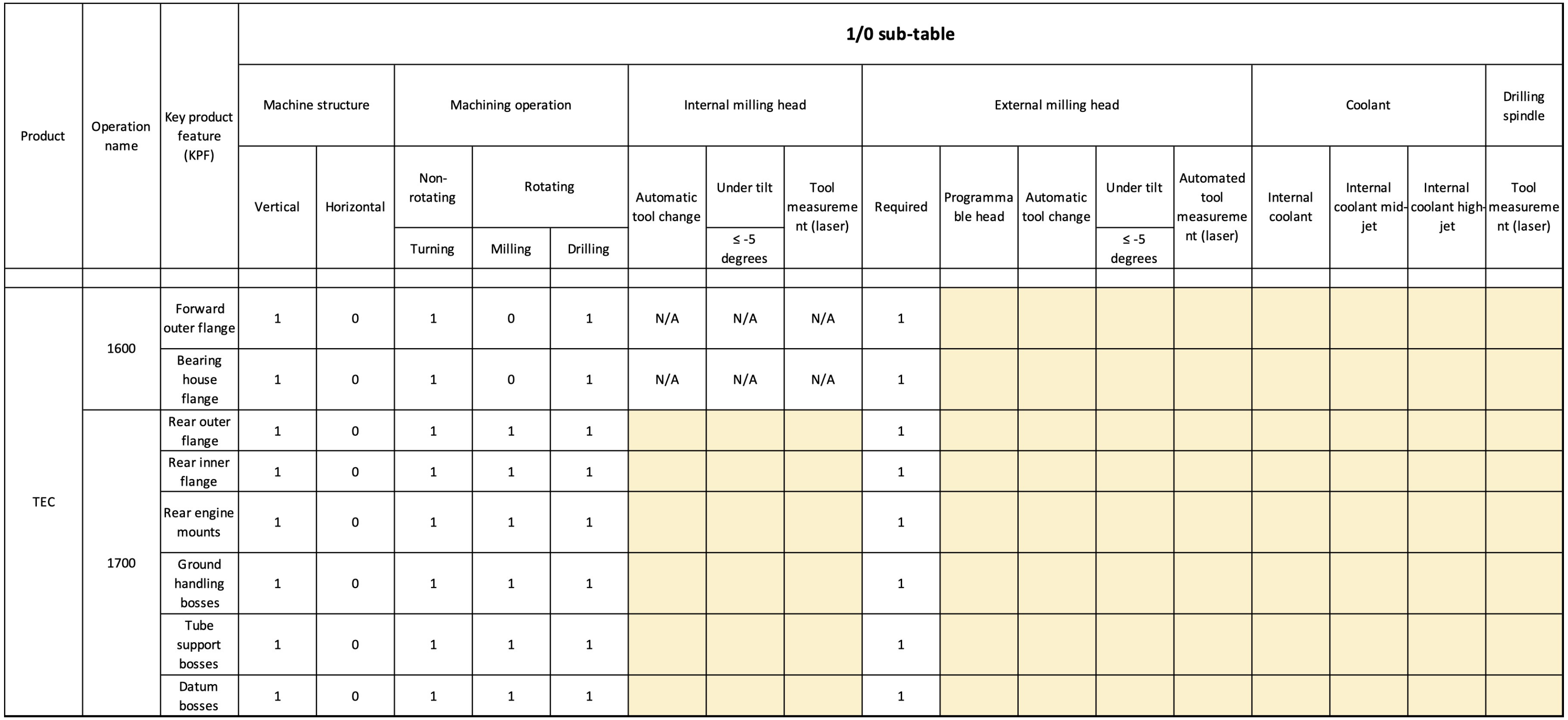
Hard constraint	**Soft constraint**
Structure	Number of touch probes
Dimensionality	External milling head (required and speed)
Machining operation	Internal coolant pressure
Tool magazine size	Rotary table max speed



Threshold sub-table

Product	Operation name	Key product feature (KPF)	Dimentionality			Tool magazine size			Number of axes of motion	Internal milling head		External milling head		Internal coolant pressure [bar]	Tool length [mm]	Rotary table max speed [rpm]	Drilling spindle speed [rpm]
			Max part diameter [mm]	Min inside diameter (ID) [mm]	Max height [mm]	Number of non-rotating tools	Number of rotating tools	Number of touch probes		Speed [rpm]	Torque [Nm]	Speed [rpm]	Torque [Nm]				
TEC	1600	Forward outer flange	1000		325	14	15	3		N/A		2000		70		20	
		Bearing house flange	1000		325	14	15	3		N/A		2000		70		20	
	1700	Rear outer flange	1000		325	8	47	2		4103				70		30	
		Rear inner flange	1000		325	8	47	2		4103				70		30	
		Rear engine mounts	1000		325	8	47	2		4103				70		30	
		Ground handling bosses	1000		325	8	47	2		4103				70		30	
		Tube support bosses	1000		325	8	47	2		4103				70		30	
		Datum bosses	1000		325	8	47	2		4103				70		30	
Threshold values TEC	1600		1000		325	14	15	3		N/A		2000		70		20	
	1700		1000		325	8	47	2		4103				70		30	

Figure 5.9: The threshold sub-table for the TEC

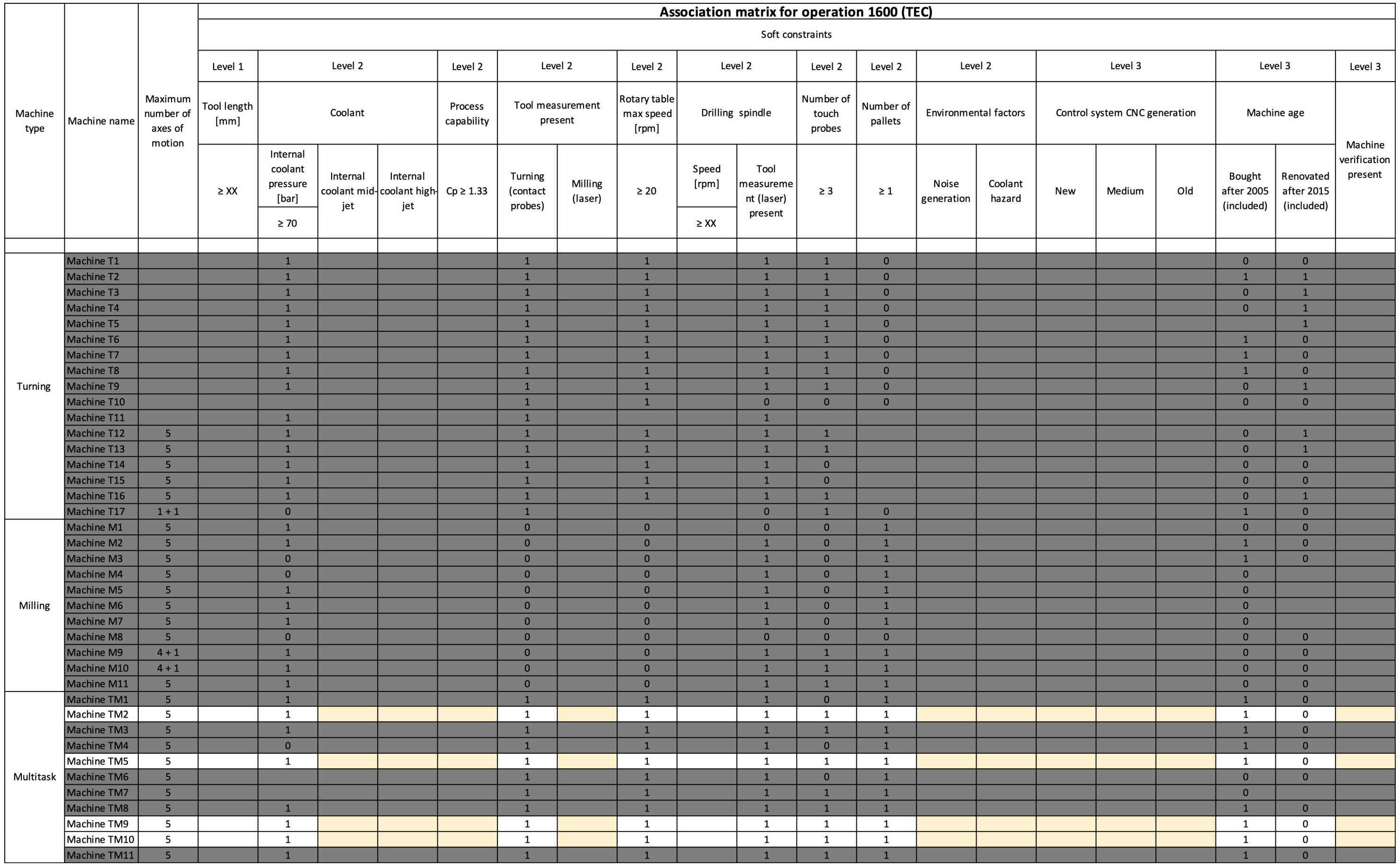


Product	Operation name	Key product feature (KPF)	1/0 sub-table																
			Machine structure		Machining operation			Internal milling head			External milling head					Coolant			Drilling spindle
			Vertical	Horizontal	Non-rotating	Rotating		Automatic tool change	Under tilt	Tool measurement (laser)	Required	Programmable head	Automatic tool change	Under tilt	Automated tool measurement (laser)	Internal coolant	Internal coolant mid-jet	Internal coolant high-jet	Tool measurement (laser)
					Turning	Milling	Drilling		≤ -5 degrees					≤ -5 degrees					
TEC	1600	Forward outer flange	1	0	1	0	1	N/A	N/A	N/A	1								
		Bearing house flange	1	0	1	0	1	N/A	N/A	N/A	1								
	1700	Rear outer flange	1	0	1	1	1				1								
		Rear inner flange	1	0	1	1	1				1								
		Rear engine mounts	1	0	1	1	1				1								
		Ground handling bosses	1	0	1	1	1				1								
		Tube support bosses	1	0	1	1	1				1								
		Datum bosses	1	0	1	1	1				1								

Figure 5.10: The 1/0 sub-table for the TEC

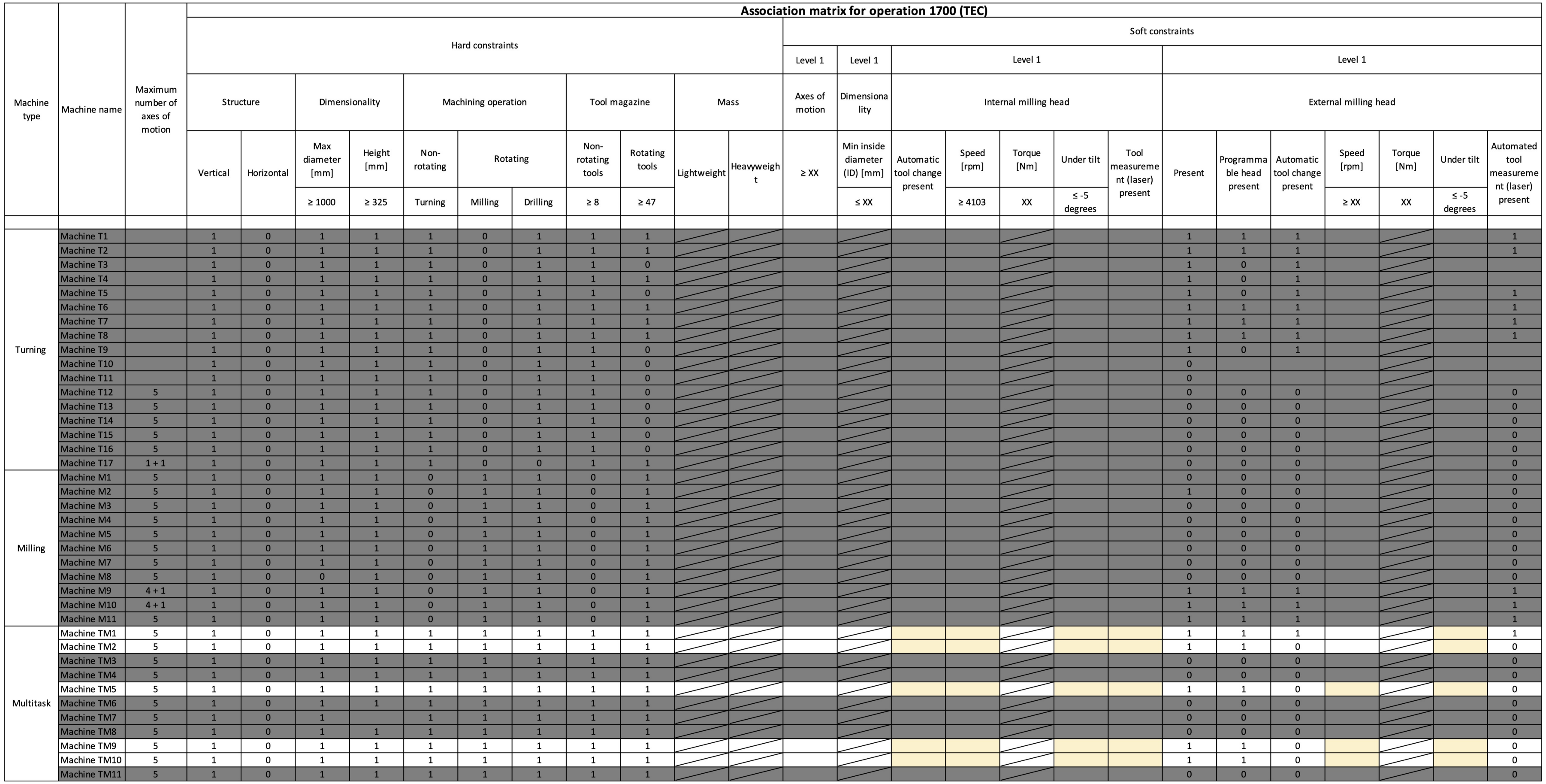
Machine type	Machine name	Maximum number of axes of motion	Association matrix for operation 1600 (TEC)																								
			Hard constraints											Soft constraints													
														Level 1	Level 1	Level 1					Level 1						
			Structure		Dimensionality		Machining operation			Tool magazine		Mass		Axes of motion	Dimensionality	Internal milling head					External milling head						
			Vertical	Horizontal	Max diameter [mm]	Height [mm]	Non-rotating	Rotating		Non-rotating tools	Rotating tools	Lightweight	Heavyweight	≥ XX	Min inside diameter (ID) [mm]	Automatic tool change present	Speed [rpm]	Torque [Nm]	Under tilt	Tool measurement (laser) present	Present	Programmable head present	Automatic tool change present	Speed [rpm]	Torque [Nm]	Under tilt	Automated tool measurement (laser) present
					≥ 1000	≥ 325	Turning	Milling	Drilling	≥ 14	≥ 15				≤ XX		≥ XX	XX	≤ -5 degrees					≥ 2000	XX	≤ -5 degrees	
Turning	Machine T1		1	0	1	1	1	0	1	1	1										1	1	1	1			1
	Machine T2		1	0	1	1	1	0	1	1	1										1	1	1	1			1
	Machine T3		1	0	1	1	1	0	1	1	1										1	0	1	1			
	Machine T4		1	0	1	1	1	0	1	1	1										1	0	1	1			
	Machine T5		1	0	1	1	1	0	1	1	1										1	0	1	1			1
	Machine T6		1	0	1	1	1	0	1	1	1										1	1	1	1			1
	Machine T7		1	0	1	1	1	0	1	1	1										1	1	1	1			1
	Machine T8		1	0	1	1	1	0	1	1	1										1	1	1	1			1
	Machine T9		1	0	1	1	1	0	1	1	1										1	0	1	1			
	Machine T10		1	0	1	1	1	0	1	1	0										0			0			
	Machine T11		1	0	1	1	1	0	1	1	1										0			0			
	Machine T12	5	1	0	1	1	1	0	1	1	1										0	0	0	0			0
	Machine T13	5	1	0	1	1	1	0	1	1	1										0	0	0	0			0
	Machine T14	5	1	0	1	1	1	0	1	1	1										0	0	0	0			0
	Machine T15	5	1	0	1	1	1	0	1	1	1										0	0	0	0			0
	Machine T16	5	1	0	1	1	1	0	1	1	1										0	0	0	0			0
	Machine T17	1 + 1	1	0	1	1	1	0	0	1	1										0	0	0	0			0
Milling	Machine M1	5	1	0	1	1	0	1	1	0	1										0	0	0	0			0
	Machine M2	5	1	0	1	1	0	1	1	0	1										1	0	0	0			0
	Machine M3	5	1	0	1	1	0	1	1	0	1										0	0	0	0			0
	Machine M4	5	1	0	1	1	0	1	1	0	1										0	0	0	0			0
	Machine M5	5	1	0	1	1	0	1	1	0	1										0	0	0	0			0
	Machine M6	5	1	0	1	1	0	1	1	0	1										0	0	0	0			0
	Machine M7	5	1	0	1	1	0	1	1	0	1										0	0	0	0			0
	Machine M8	5	1	0	0	1	0	1	1	0	1										0	0	0	0			0
	Machine M9	4 + 1	1	0	1	1	0	1	1	0	1										1	1	1	1			1
	Machine M10	4 + 1	1	0	1	1	0	1	1	0	1										1	1	1	1			1
	Machine M11	5	1	0	1	1	0	1	1	0	1										1	1	1	1			1
Multitask	Machine TM1	5	1	0	1	1	1	1	1	1	1										1	1	1	1			1
	Machine TM2	5	1	0	1	1	1	1	1	1	1										1	1	0	1			0
	Machine TM3	5	1	0	1	1	1	1	1	1	1										0	0	0	0			0
	Machine TM4	5	1	0	1	1	1	1	1	1	1										0	0	0	0			0
	Machine TM5	5	1	0	1	1	1	1	1	1	1										1	1	0	1			0
	Machine TM6	5	1	0	1	1	1	1	1	1	1										0	0	0	0			0
	Machine TM7	5	1	0	1		1	1	1	1	1										0	0	0	0			0
	Machine TM8	5	1	0	1	1	1	1	1	1	1										0	0	0	0			0
	Machine TM9	5	1	0	1	1	1	1	1	1	1										1	1	0	1			0
	Machine TM10	5	1	0	1	1	1	1	1	1	1										1	1	0	1			0
	Machine TM11	5	1	0	1	1	1	1	1	1	1										0	0	0	0			0

Figure 5.11: The association matrix for operation 1600 (part 1)



Machine type	Machine name	Maximum number of axes of motion	Association matrix for operation 1600 (TEC)																			
			Soft constraints																			
			Level 1	Level 2			Level 2	Level 2		Level 2	Level 2		Level 2	Level 2	Level 2		Level 3			Level 3		Level 3
			Tool length [mm]	Coolant			Process capability	Tool measurement present		Rotary table max speed [rpm]	Drilling spindle		Number of touch probes	Number of pallets	Environmental factors		Control system CNC generation			Machine age		Machine verification present
			≥ XX	Internal coolant pressure [bar]	Internal coolant mid-jet	Internal coolant high-jet	Cp ≥ 1.33	Turning (contact probes)	Milling (laser)	≥ 20	Speed [rpm]	Tool measurement (laser) present	≥ 3	≥ 1	Noise generation	Coolant hazard	New	Medium	Old	Bought after 2005 (included)	Renovated after 2015 (included)	
				≥ 70							≥ XX											
Turning	Machine T1			1				1		1		1	1	0						0	0	
	Machine T2			1				1		1		1	1	0						1	1	
	Machine T3			1				1		1		1	1	0						0	1	
	Machine T4			1				1		1		1	1	0						0	1	
	Machine T5			1				1		1		1	1	0							1	
	Machine T6			1				1		1		1	1	0						1	0	
	Machine T7			1				1		1		1	1	0						1	0	
	Machine T8			1				1		1		1	1	0						1	0	
	Machine T9			1				1		1		1	1	0						0	1	
	Machine T10							1		1		0	0	0						0	0	
	Machine T11			1				1				1										
	Machine T12	5		1				1		1		1	1							0	1	
	Machine T13	5		1				1		1		1	1							0	1	
	Machine T14	5		1				1		1		1	0							0	0	
	Machine T15	5		1				1		1		1	0							0	0	
	Machine T16	5		1				1		1		1	1							0	1	
	Machine T17	1 + 1		0				1				0	1	0						1	0	
Milling	Machine M1	5		1				0		0		0	0	1						0	0	
	Machine M2	5		1				0		0		1	0	1						1	0	
	Machine M3	5		0				0		0		1	0	1						1	0	
	Machine M4	5		0				0		0		1	0	1						0		
	Machine M5	5		1				0		0		1	0	1						0		
	Machine M6	5		1				0		0		1	0	1						0		
	Machine M7	5		1				0		0		1	0	1						0		
	Machine M8	5		0				0		0		0	0	0						0	0	
	Machine M9	4 + 1		1				0		0		1	1	1						0	0	
	Machine M10	4 + 1		1				0		0		1	1	1						0	0	
	Machine M11	5		1				0		0		1	1	1						0	0	
Multitask	Machine TM1	5		1				1		1		1	0	1						1	0	
	Machine TM2	5		1				1		1		1	1	1						1	0	
	Machine TM3	5		1				1		1		1	1	1						1	0	
	Machine TM4	5		0				1		1		1	0	1						1	0	
	Machine TM5	5		1				1		1		1	1	1						1	0	
	Machine TM6	5						1		1		1	0	1						0	0	
	Machine TM7	5						1		1		1	1	1						0		
	Machine TM8	5		1				1		1		1	1	1						1	0	
	Machine TM9	5		1				1		1		1	1	1						1	0	
	Machine TM10	5		1				1		1		1	1	1						1	0	
	Machine TM11	5		1				1		1		1	1	1						1	0	

Figure 5.12: The association matrix for operation 1600 (part 2)



Machine type	Machine name	Maximum number of axes of motion	Association matrix for operation 1700 (TEC)																								
			Hard constraints											Soft constraints													
														Level 1	Level 1	Level 1					Level 1						
			Structure		Dimensionality		Machining operation			Tool magazine		Mass		Axes of motion	Dimensionality	Internal milling head					External milling head						
			Vertical	Horizontal	Max diameter [mm]	Height [mm]	Non-rotating	Rotating		Non-rotating tools	Rotating tools	Lightweight	Heavyweight		Min inside diameter (ID) [mm]	Automatic tool change present	Speed [rpm]	Torque [Nm]	Under tilt	Tool measurement (laser) present	Present	Programmable head present	Automatic tool change present	Speed [rpm]	Torque [Nm]	Under tilt	Automated tool measurement (laser) present
					≥ 1000	≥ 325	Turning	Milling	Drilling	≥ 8	≥ 47			≥ XX	≤ XX		≥ 4103	XX	≤ -5 degrees					≥ XX	XX	≤ -5 degrees	
Turning	Machine T1		1	0	1	1	1	0	1	1	1										1	1	1				1
	Machine T2		1	0	1	1	1	0	1	1	1										1	1	1				1
	Machine T3		1	0	1	1	1	0	1	1	0										1	0	1				
	Machine T4		1	0	1	1	1	0	1	1	1										1	0	1				
	Machine T5		1	0	1	1	1	0	1	1	0										1	0	1				1
	Machine T6		1	0	1	1	1	0	1	1	1										1	1	1				1
	Machine T7		1	0	1	1	1	0	1	1	1										1	1	1				1
	Machine T8		1	0	1	1	1	0	1	1	1										1	1	1				1
	Machine T9		1	0	1	1	1	0	1	1	0										1	0	1				
	Machine T10		1	0	1	1	1	0	1	1	0										0						
	Machine T11		1	0	1	1	1	0	1	1	0										0						
	Machine T12	5	1	0	1	1	1	0	1	1	0										0	0	0				0
	Machine T13	5	1	0	1	1	1	0	1	1	0										0	0	0				0
	Machine T14	5	1	0	1	1	1	0	1	1	0										0	0	0				0
	Machine T15	5	1	0	1	1	1	0	1	1	0										0	0	0				0
	Machine T16	5	1	0	1	1	1	0	1	1	0										0	0	0				0
	Machine T17	1 + 1	1	0	1	1	1	0	0	1	1										0	0	0				0
Milling	Machine M1	5	1	0	1	1	0	1	1	0	1										0	0	0				0
	Machine M2	5	1	0	1	1	0	1	1	0	1										1	0	0				0
	Machine M3	5	1	0	1	1	0	1	1	0	1										0	0	0				0
	Machine M4	5	1	0	1	1	0	1	1	0	1										0	0	0				0
	Machine M5	5	1	0	1	1	0	1	1	0	1										0	0	0				0
	Machine M6	5	1	0	1	1	0	1	1	0	1										0	0	0				0
	Machine M7	5	1	0	1	1	0	1	1	0	1										0	0	0				0
	Machine M8	5	1	0	0	1	0	1	1	0	1										0	0	0				0
	Machine M9	4 + 1	1	0	1	1	0	1	1	0	1										1	1	1				1
	Machine M10	4 + 1	1	0	1	1	0	1	1	0	1										1	1	1				1
	Machine M11	5	1	0	1	1	0	1	1	0	1										1	1	1				1
Multitask	Machine TM1	5	1	0	1	1	1	1	1	1	1										1	1	1				1
	Machine TM2	5	1	0	1	1	1	1	1	1	1										1	1	0				0
	Machine TM3	5	1	0	1	1	1	1	1	1	1										0	0	0				0
	Machine TM4	5	1	0	1	1	1	1	1	1	1										0	0	0				0
	Machine TM5	5	1	0	1	1	1	1	1	1	1										1	1	0				0
	Machine TM6	5	1	0	1	1	1	1	1	1	1										0	0	0				0
	Machine TM7	5	1	0	1		1	1	1	1	1										0	0	0				0
	Machine TM8	5	1	0	1	1	1	1	1	1	1										0	0	0				0
	Machine TM9	5	1	0	1	1	1	1	1	1	1										1	1	0				0
	Machine TM10	5	1	0	1	1	1	1	1	1	1										1	1	0				0
	Machine TM11	5	1	0	1	1	1	1	1	1	1										0	0	0				0

Figure 5.13: The association matrix for operation 1700 (part 1)

			Association matrix for operation 1700 (TEC)																			
			Soft constraints																			
			Level 1	Level 2			Level 2	Level 2		Level 2	Level 2		Level 2	Level 2	Level 2		Level 3			Level 3		Level 3
Machine type	Machine name	Maximum number of axes of motion	Tool length [mm]	Coolant			Process capability	Tool measurement present		Rotary table max speed [rpm]	Drilling spindle		Number of touch probes	Number of pallets	Environmental factors		Control system CNC generation			Machine age		Machine verification present
			≥ XX	Internal coolant pressure [bar]	Internal coolant mid-jet	Internal coolant high-jet	Cp ≥ 1.33	Turning (contact probes)	Milling (laser)	≥ 30	Speed [rpm]	Tool measurement (laser) present	≥ 2	≥ 1	Noise generation	Coolant hazard	New	Medium	Old	Bought after 2005 (included)	Renovated after 2015 (included)	
				≥ 70							≥ XX											
Turning	Machine T1			1				1		1		1	1	0						0	0	
	Machine T2			1				1		1		1	1	0						1	1	
	Machine T3			1				1		1		1	1	0						0	1	
	Machine T4			1				1		1		1	1	0						0	1	
	Machine T5			1				1		1		1	1	0							1	
	Machine T6			1				1		1		1	1	0						1	0	
	Machine T7			1				1		1		1	1	0						1	0	
	Machine T8			1				1		1		1	1	0						1	0	
	Machine T9			1				1		1		1	1	0						0	1	
	Machine T10							1		1		0	0	0						0	0	
	Machine T11			1				1				1										
	Machine T12	5		1				1		1		1	1							0	1	
	Machine T13	5		1				1		1		1	1							0	1	
	Machine T14	5		1				1		1		1	1							0	0	
	Machine T15	5		1				1		1		1	0							0	0	
	Machine T16	5		1				1		1		1	1							0	1	
	Machine T17	1 + 1		0				1				0	1	0						1	0	
Milling	Machine M1	5		1				0		0		0	0	1						0	0	
	Machine M2	5		1				0		0		1	1	1						1	0	
	Machine M3	5		0				0		0		1	1	1						1	0	
	Machine M4	5		0				0		0		1	0	1						0		
	Machine M5	5		1				0		0		1	0	1						0		
	Machine M6	5		1				0		0		1	0	1						0		
	Machine M7	5		1				0		0		1	0	1						0		
	Machine M8	5		0				0		0		0	0	0						0	0	
	Machine M9	4 + 1		1				0		0		1	1	1						0	0	
	Machine M10	4 + 1		1				0		0		1	1	1						0	0	
	Machine M11	5		1				0		0		1	1	1						0	0	
Multitask	Machine TM1	5		1				1		0		1	1	1						1	0	
	Machine TM2	5		1				1		1		1	1	1						1	0	
	Machine TM3	5		1				1		1		1	1	1						1	0	
	Machine TM4	5		0				1		1		1	1	1						1	0	
	Machine TM5	5		1				1		1		1	1	1						1	0	
	Machine TM6	5						1		1		1	1	1						0	0	
	Machine TM7	5						1		1		1	1	1						0		
	Machine TM8	5		1				1		1		1	1	1						1	0	
	Machine TM9	5		1				1		1		1	1	1						1	0	
	Machine TM10	5		1				1		1		1	1	1						1	0	
	Machine TM11	5		1				1		1		1	1	1						1	0	

Figure 5.14: The association matrix for operation 1700 (part 2)

5.6.2 LPT case

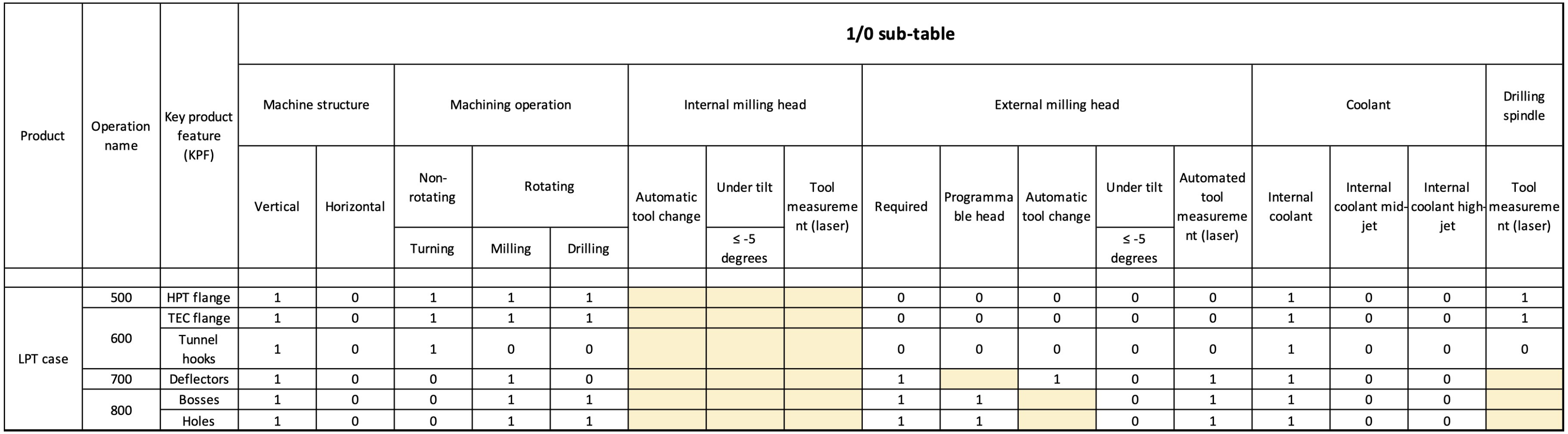
The same process described in Section 5.6.1 was executed for operations 500, 600, 700 and 800 of the LPT case. Figure 5.15 and Figure 5.16 show the threshold sub-table and the 1/0 sub-table respectively. Figure 5.15 also shows the threshold values determined for operations 500, 600, 700 and 800. These threshold values are substituted in place of XX in the KMCs table, determining an association matrix for each of the four operations. The hard and soft constraints used to run the model for the LPT case are shown in Table 5.7. Figures 5.17 and 5.18, Figures 5.19 and 5.20, Figures 5.21 and 5.22 and Figures 5.23 and 5.24 show the results of the process, revealing the machines selected for operations 500, 600, 700 and 800 respectively.

Table 5.7: The hard and soft constraints used to run the model for the LPT case

Hard constraint	**Soft constraint**
Structure	Number of touch probes
Dimensionality	Number of axes of motion
Machining operation	External milling head (all parameters)
Tool magazine size	Internal coolant pressure
	Tool length
	Rotary table max speed
	Drilling spindle speed
	Coolant
	Drilling spindle (tool measurement)

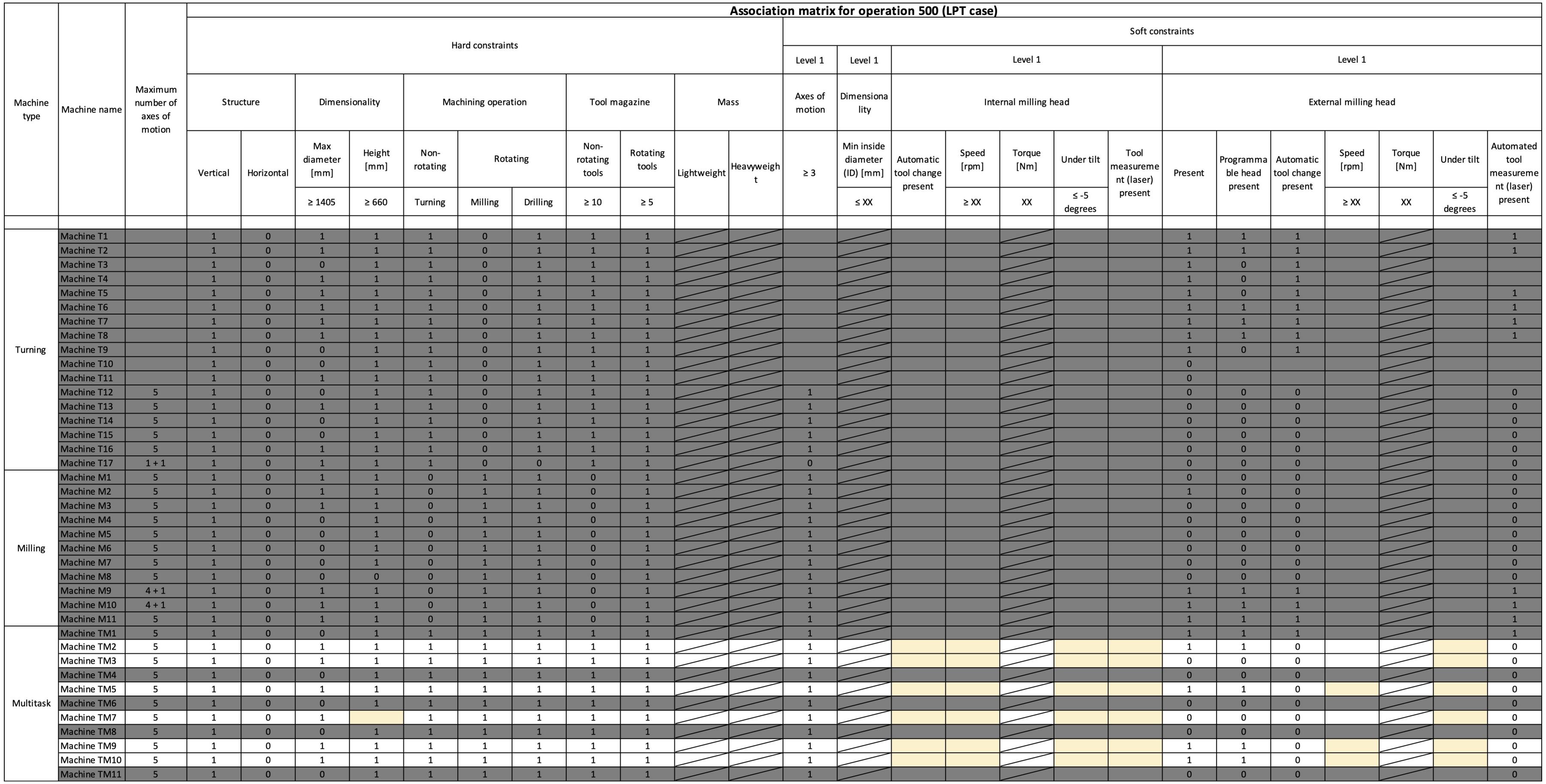
Product	Operation name	Key product feature (KPF)	Threshold sub-table													
			Dimentionality			Tool magazine size			Number of axes of motion	Internal milling head		External milling head		Internal coolant pressure [bar]	Tool length [mm]	Rotary table max speed [rpm]	Drilling spindle speed [rpm]
			Max part diameter [mm]	Min inside diameter (ID) [mm]	Max height [mm]	Number of non-rotating tools	Number of rotating tools	Number of touch probes		Speed [rpm]	Torque [Nm]	Speed [rpm]	Torque [Nm]				
LPT case	500	HPT flange	1405	N/A	660	10	5	1	3					70	250	100	2000
	600	TEC flange	1405	N/A	660	12	4	1	3					70	250	100	2000
		Tunnel hooks	1405	915	660	16	N/A	2	2					70	250	25	N/A
	700	Deflectors	1405	1330	660	N/A	9	1	3								885
	800	Bosses	1405	N/A	660	N/A	62	1	3								4168
		Holes	1405	N/A	660	N/A	62	1	3								4168
Threshold values LPT case	500		1405	N/A	660	10	5	1	3					70	250	100	2000
	600		1405	915	660	16	4	2	3					70	250	100	2000
	700		1405	1330	660	N/A	10	1	3								885
	800		1405	N/A	660	N/A	63	1	3								4168

Figure 5.15: The threshold sub-table for the LPT case



Product	Operation name	Key product feature (KPF)	1/0 sub-table																
			Machine structure		Machining operation			Internal milling head			External milling head					Coolant			Drilling spindle
			Vertical	Horizontal	Non-rotating	Rotating		Automatic tool change	Under tilt	Tool measurement (laser)	Required	Programmable head	Automatic tool change	Under tilt	Automated tool measurement (laser)	Internal coolant	Internal coolant mid-jet	Internal coolant high-jet	Tool measurement (laser)
					Turning	Milling	Drilling		≤ -5 degrees					≤ -5 degrees					
LPT case	500	HPT flange	1	0	1	1	1				0	0	0	0	0	1	0	0	1
	600	TEC flange	1	0	1	1	1				0	0	0	0	0	1	0	0	1
		Tunnel hooks	1	0	1	0	0				0	0	0	0	0	1	0	0	0
	700	Deflectors	1	0	0	1	0				1		1	0	1	1	0	0	
	800	Bosses	1	0	0	1	1				1	1		0	1	1	0	0	
		Holes	1	0	0	1	1				1	1		0	1	1	0	0	

Figure 5.16: The 1/0 sub-table for the LPT case

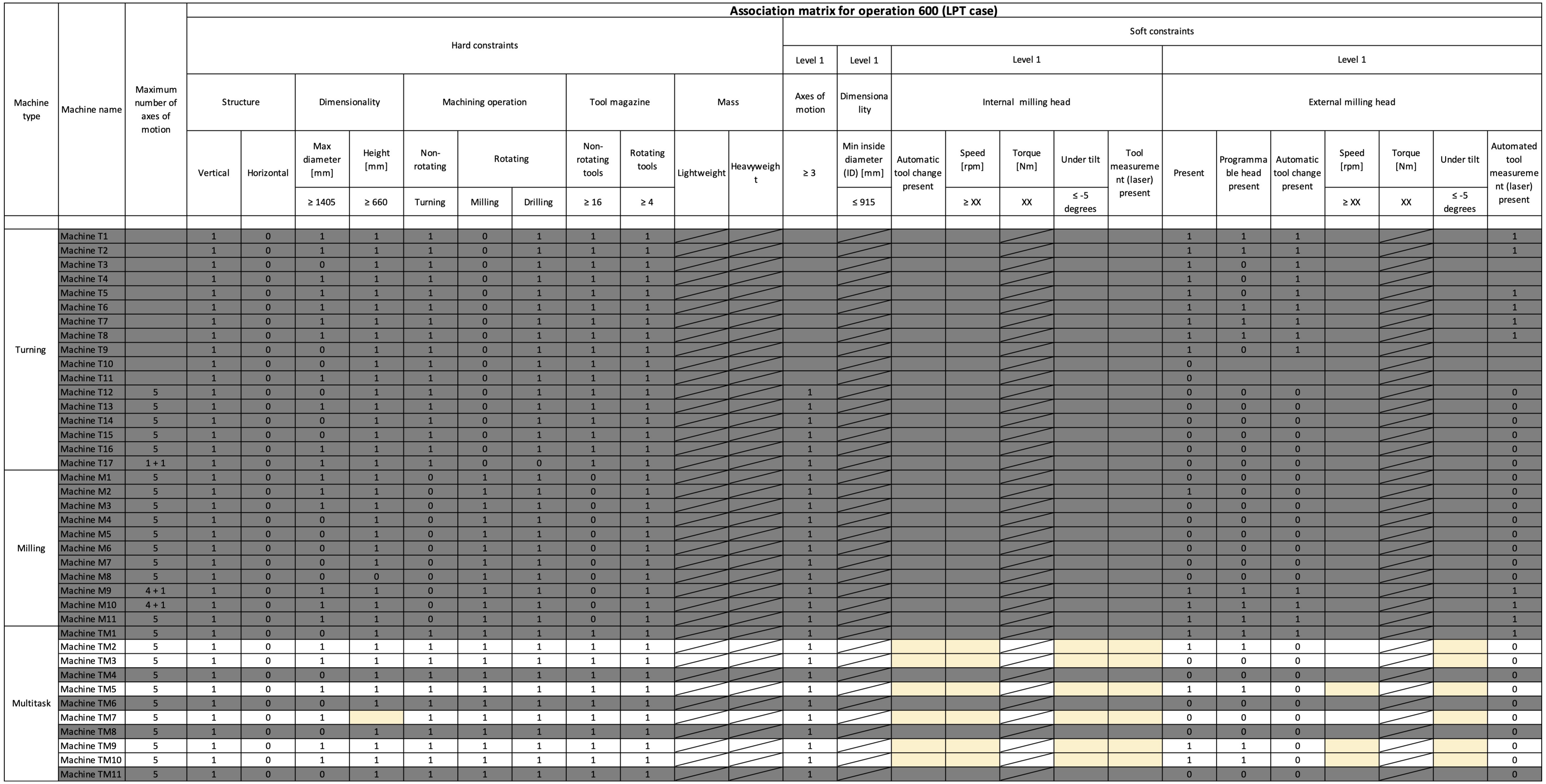


Machine type	Machine name	Maximum number of axes of motion	Association matrix for operation 500 (LPT case)																								
			Hard constraints											Soft constraints													
														Level 1	Level 1	Level 1					Level 1						
			Structure		Dimensionality		Machining operation			Tool magazine		Mass		Axes of motion	Dimensionality	Internal milling head					External milling head						
			Vertical	Horizontal	Max diameter [mm]	Height [mm]	Non-rotating	Rotating		Non-rotating tools	Rotating tools	Lightweight	Heavyweight	≥ 3	Min inside diameter (ID) [mm]	Automatic tool change present	Speed [rpm]	Torque [Nm]	Under tilt	Tool measurement (laser) present	Present	Programmable head present	Automatic tool change present	Speed [rpm]	Torque [Nm]	Under tilt	Automated tool measurement (laser) present
					≥ 1405	≥ 660	Turning	Milling	Drilling	≥ 10	≥ 5				≤ XX		≥ XX	XX	≤ -5 degrees					≥ XX	XX	≤ -5 degrees	
Turning	Machine T1		1	0	1	1	1	0	1	1	1										1	1	1				1
	Machine T2		1	0	1	1	1	0	1	1	1										1	1	1				1
	Machine T3		1	0	0	1	1	0	1	1	1										1	0	1				
	Machine T4		1	0	1	1	1	0	1	1	1										1	0	1				
	Machine T5		1	0	1	1	1	0	1	1	1										1	0	1				1
	Machine T6		1	0	1	1	1	0	1	1	1										1	1	1				1
	Machine T7		1	0	1	1	1	0	1	1	1										1	1	1				1
	Machine T8		1	0	1	1	1	0	1	1	1										1	1	1				1
	Machine T9		1	0	0	1	1	0	1	1	1										1	0	1				
	Machine T10		1	0	0	1	1	0	1	1	1										0						
	Machine T11		1	0	1	1	1	0	1	1	1										0						
	Machine T12	5	1	0	0	1	1	0	1	1	1			1							0	0	0				0
	Machine T13	5	1	0	1	1	1	0	1	1	1			1							0	0	0				0
	Machine T14	5	1	0	0	1	1	0	1	1	1			1							0	0	0				0
	Machine T15	5	1	0	0	1	1	0	1	1	1			1							0	0	0				0
	Machine T16	5	1	0	1	1	1	0	1	1	1			1							0	0	0				0
	Machine T17	1 + 1	1	0	1	1	1	0	0	1	1			0							0	0	0				0
Milling	Machine M1	5	1	0	1	1	0	1	1	0	1			1							0	0	0				0
	Machine M2	5	1	0	1	1	0	1	1	0	1			1							1	0	0				0
	Machine M3	5	1	0	1	1	0	1	1	0	1			1							0	0	0				0
	Machine M4	5	1	0	0	1	0	1	1	0	1			1							0	0	0				0
	Machine M5	5	1	0	0	1	0	1	1	0	1			1							0	0	0				0
	Machine M6	5	1	0	0	1	0	1	1	0	1			1							0	0	0				0
	Machine M7	5	1	0	0	1	0	1	1	0	1			1							0	0	0				0
	Machine M8	5	1	0	0	0	0	1	1	0	1			1							0	0	0				0
	Machine M9	4 + 1	1	0	1	1	0	1	1	0	1			1							1	1	1				1
	Machine M10	4 + 1	1	0	1	1	0	1	1	0	1			1							1	1	1				1
	Machine M11	5	1	0	1	1	0	1	1	0	1			1							1	1	1				1
Multitask	Machine TM1	5	1	0	0	1	1	1	1	1	1			1							1	1	1				1
	Machine TM2	5	1	0	1	1	1	1	1	1	1			1							1	1	0				0
	Machine TM3	5	1	0	1	1	1	1	1	1	1			1							0	0	0				0
	Machine TM4	5	1	0	0	1	1	1	1	1	1			1							0	0	0				0
	Machine TM5	5	1	0	1	1	1	1	1	1	1			1							1	1	0				0
	Machine TM6	5	1	0	0	1	1	1	1	1	1			1							0	0	0				0
	Machine TM7	5	1	0	1		1	1	1	1	1			1							0	0	0				0
	Machine TM8	5	1	0	0	1	1	1	1	1	1			1							0	0	0				0
	Machine TM9	5	1	0	1	1	1	1	1	1	1			1							1	1	0				0
	Machine TM10	5	1	0	1	1	1	1	1	1	1			1							1	1	0				0
	Machine TM11	5	1	0	0	1	1	1	1	1	1			1							0	0	0				0

Figure 5.17: The association matrix for operation 500 (part 1)

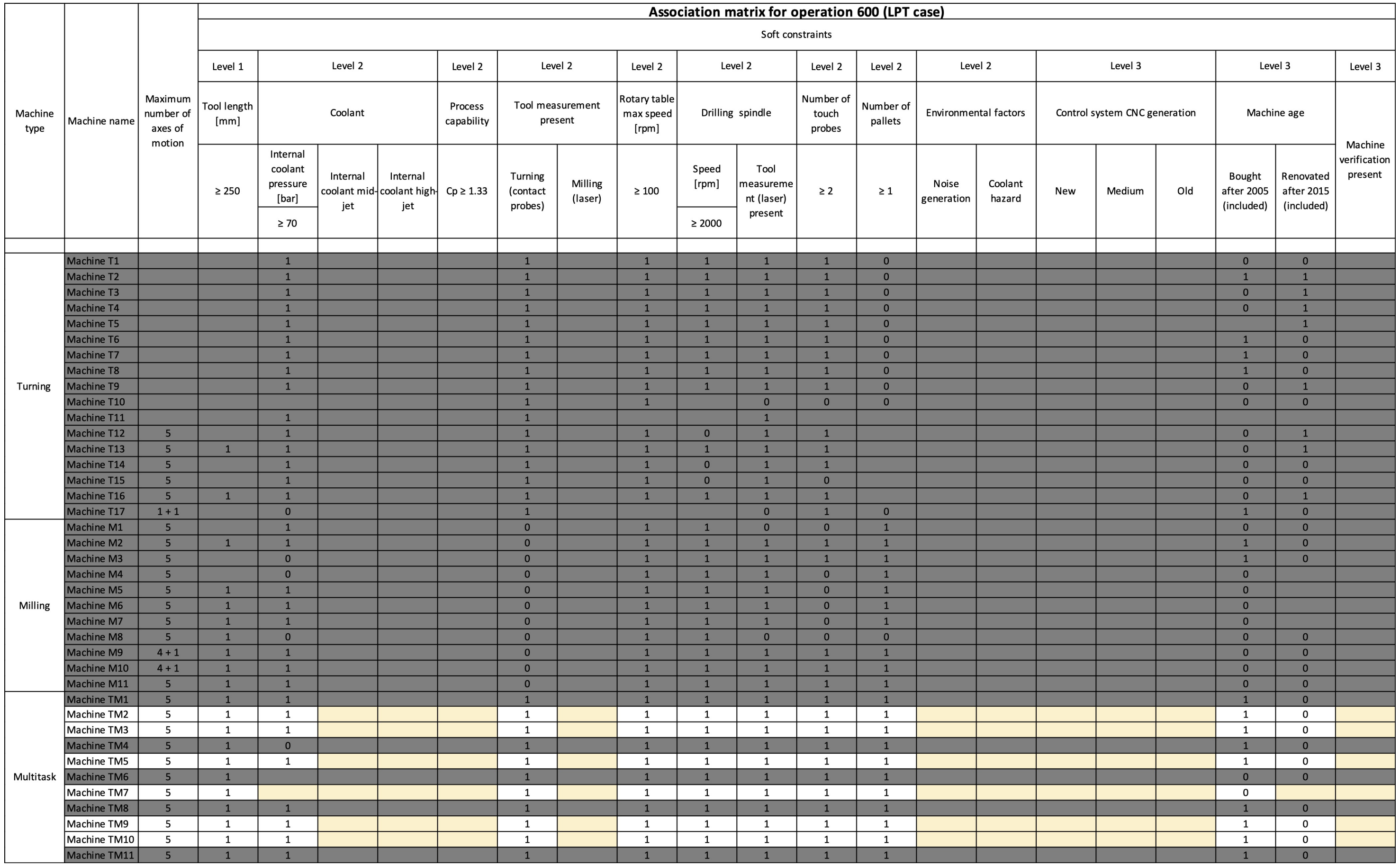
Machine type	Machine name	Maximum number of axes of motion	Association matrix for operation 500 (LPT case)																			
			Soft constraints																			
			Level 1	Level 2			Level 2	Level 2		Level 2	Level 2		Level 2	Level 2	Level 2		Level 3			Level 3		Level 3
			Tool length [mm]	Coolant			Process capability	Tool measurement present		Rotary table max speed [rpm]	Drilling spindle		Number of touch probes	Number of pallets	Environmental factors		Control system CNC generation			Machine age		Machine verification present
			≥ 250	Internal coolant pressure [bar]	Internal coolant mid-jet	Internal coolant high-jet	Cp ≥ 1.33	Turning (contact probes)	Milling (laser)	≥ 100	Speed [rpm]	Tool measurement (laser) present	≥ 1	≥ 1	Noise generation	Coolant hazard	New	Medium	Old	Bought after 2005 (included)	Renovated after 2015 (included)	
				≥ 70							≥ 2000											
Turning	Machine T1			1				1		1	1	1	1	0						0	0	
	Machine T2			1				1		1	1	1	1	0						1	1	
	Machine T3			1				1		1	1	1	1	0						0	1	
	Machine T4			1				1		1	1	1	1	0						0	1	
	Machine T5			1				1		1	1	1	1	0							1	
	Machine T6			1				1		1	1	1	1	0						1	0	
	Machine T7			1				1		1	1	1	1	0						1	0	
	Machine T8			1				1		1	1	1	1	0						1	0	
	Machine T9			1				1		1	1	1	1	0						0	1	
	Machine T10							1		1		0	0	0						0	0	
	Machine T11			1				1				1										
	Machine T12	5		1				1		1	0	1	1							0	1	
	Machine T13	5	1	1				1		1	1	1	1							0	1	
	Machine T14	5		1				1		1	0	1	1							0	0	
	Machine T15	5		1				1		1	0	1	1							0	0	
	Machine T16	5	1	1				1		1	1	1	1							0	1	
	Machine T17	1 + 1		0				1				0	1	0						1	0	
Milling	Machine M1	5		1				0		1	1	0	1	1						0	0	
	Machine M2	5	1	1				0		1	1	1	1	1						1	0	
	Machine M3	5		0				0		1	1	1	1	1						1	0	
	Machine M4	5		0				0		1	1	1	1	1						0		
	Machine M5	5	1	1				0		1	1	1	1	1						0		
	Machine M6	5	1	1				0		1	1	1	1	1						0		
	Machine M7	5	1	1				0		1	1	1	1	1						0		
	Machine M8	5	1	0				0		1	1	0	1	0						0	0	
	Machine M9	4 + 1	1	1				0		1	1	1	1	1						0	0	
	Machine M10	4 + 1	1	1				0		1	1	1	1	1						0	0	
	Machine M11	5	1	1				0		1	1	1	1	1						0	0	
Multitask	Machine TM1	5	1	1				1		1	1	1	1	1						1	0	
	Machine TM2	5	1	1				1		1	1	1	1	1						1	0	
	Machine TM3	5	1	1				1		1	1	1	1	1						1	0	
	Machine TM4	5	1	0				1		1	1	1	1	1						1	0	
	Machine TM5	5	1	1				1		1	1	1	1	1						1	0	
	Machine TM6	5	1					1		1	1	1	1	1						0	0	
	Machine TM7	5	1					1		1	1	1	1	1						0		
	Machine TM8	5	1	1				1		1	1	1	1	1						1	0	
	Machine TM9	5	1	1				1		1	1	1	1	1						1	0	
	Machine TM10	5	1	1				1		1	1	1	1	1						1	0	
	Machine TM11	5	1	1				1		1	1	1	1	1						1	0	

Figure 5.18: The association matrix for operation 500 (part 2)



Machine type	Machine name	Maximum number of axes of motion	Association matrix for operation 600 (LPT case)																								
			Hard constraints											Soft constraints													
														Level 1	Level 1	Level 1					Level 1						
			Structure		Dimensionality		Machining operation			Tool magazine		Mass		Axes of motion	Dimensionality	Internal milling head					External milling head						
			Vertical	Horizontal	Max diameter [mm]	Height [mm]	Non-rotating	Rotating		Non-rotating tools	Rotating tools	Lightweight	Heavyweight	≥ 3	Min inside diameter (ID) [mm]	Automatic tool change present	Speed [rpm]	Torque [Nm]	Under tilt	Tool measurement (laser) present	Present	Programmable head present	Automatic tool change present	Speed [rpm]	Torque [Nm]	Under tilt	Automated tool measurement (laser) present
					≥ 1405	≥ 660	Turning	Milling	Drilling	≥ 16	≥ 4				≤ 915		≥ XX	XX	≤ -5 degrees					≥ XX	XX	≤ -5 degrees	
Turning	Machine T1		1	0	1	1	1	0	1	1	1										1	1	1				1
	Machine T2		1	0	1	1	1	0	1	1	1										1	1	1				1
	Machine T3		1	0	0	1	1	0	1	1	1										1	0	1				
	Machine T4		1	0	1	1	1	0	1	1	1										1	0	1				
	Machine T5		1	0	1	1	1	0	1	1	1										1	0	1				1
	Machine T6		1	0	1	1	1	0	1	1	1										1	1	1				1
	Machine T7		1	0	1	1	1	0	1	1	1										1	1	1				1
	Machine T8		1	0	1	1	1	0	1	1	1										1	1	1				1
	Machine T9		1	0	0	1	1	0	1	1	1										1	0	1				
	Machine T10		1	0	0	1	1	0	1	1	1										0						
	Machine T11		1	0	1	1	1	0	1	1	1										0						
	Machine T12	5	1	0	0	1	1	0	1	1	1			1							0	0	0				0
	Machine T13	5	1	0	1	1	1	0	1	1	1			1							0	0	0				0
	Machine T14	5	1	0	0	1	1	0	1	1	1			1							0	0	0				0
	Machine T15	5	1	0	0	1	1	0	1	1	1			1							0	0	0				0
	Machine T16	5	1	0	1	1	1	0	1	1	1			1							0	0	0				0
	Machine T17	1 + 1	1	0	1	1	1	0	0	1	1			1							0	0	0				0
Milling	Machine M1	5	1	0	1	1	0	1	1	0	1			1							0	0	0				0
	Machine M2	5	1	0	1	1	0	1	1	0	1			1							1	0	0				0
	Machine M3	5	1	0	1	1	0	1	1	0	1			1							0	0	0				0
	Machine M4	5	1	0	0	1	0	1	1	0	1			1							0	0	0				0
	Machine M5	5	1	0	0	1	0	1	1	0	1			1							0	0	0				0
	Machine M6	5	1	0	0	1	0	1	1	0	1			1							0	0	0				0
	Machine M7	5	1	0	0	1	0	1	1	0	1			1							0	0	0				0
	Machine M8	5	1	0	0	0	0	1	1	0	1			1							0	0	0				0
	Machine M9	4 + 1	1	0	1	1	0	1	1	0	1			1							1	1	1				1
	Machine M10	4 + 1	1	0	1	1	0	1	1	0	1			1							1	1	1				1
	Machine M11	5	1	0	1	1	0	1	1	0	1			1							1	1	1				1
Multitask	Machine TM1	5	1	0	0	1	1	1	1	1	1			1							1	1	1				1
	Machine TM2	5	1	0	1	1	1	1	1	1	1			1							1	1	0				0
	Machine TM3	5	1	0	1	1	1	1	1	1	1			1							0	0	0				0
	Machine TM4	5	1	0	0	1	1	1	1	1	1			1							0	0	0				0
	Machine TM5	5	1	0	1	1	1	1	1	1	1			1							1	1	0				0
	Machine TM6	5	1	0	0	1	1	1	1	1	1			1							0	0	0				0
	Machine TM7	5	1	0	1		1	1	1	1	1			1							0	0	0				0
	Machine TM8	5	1	0	0	1	1	1	1	1	1			1							0	0	0				0
	Machine TM9	5	1	0	1	1	1	1	1	1	1			1							1	1	0				0
	Machine TM10	5	1	0	1	1	1	1	1	1	1			1							1	1	0				0
	Machine TM11	5	1	0	0	1	1	1	1	1	1			1							0	0	0				0

Figure 5.19: The association matrix for operation 600 (part 1)



Machine type	Machine name	Maximum number of axes of motion	Association matrix for operation 600 (LPT case)																			
			Soft constraints																			
			Level 1	Level 2			Level 2	Level 2		Level 2	Level 2		Level 2	Level 2	Level 2		Level 3			Level 3		Level 3
			Tool length [mm]	Coolant			Process capability	Tool measurement present		Rotary table max speed [rpm]	Drilling spindle		Number of touch probes	Number of pallets	Environmental factors		Control system CNC generation			Machine age		Machine verification present
			≥ 250	Internal coolant pressure [bar]	Internal coolant mid-jet	Internal coolant high-jet	Cp ≥ 1.33	Turning (contact probes)	Milling (laser)	≥ 100	Speed [rpm]	Tool measurement (laser) present	≥ 2	≥ 1	Noise generation	Coolant hazard	New	Medium	Old	Bought after 2005 (included)	Renovated after 2015 (included)	
				≥ 70							≥ 2000											
Turning	Machine T1			1				1		1	1	1	1	0						0	0	
	Machine T2			1				1		1	1	1	1	0						1	1	
	Machine T3			1				1		1	1	1	1	0						0	1	
	Machine T4			1				1		1	1	1	1	0						0	1	
	Machine T5			1				1		1	1	1	1	0							1	
	Machine T6			1				1		1	1	1	1	0						1	0	
	Machine T7			1				1		1	1	1	1	0						1	0	
	Machine T8			1				1		1	1	1	1	0						1	0	
	Machine T9			1				1		1	1	1	1	0						0	1	
	Machine T10							1		1		0	0	0						0	0	
	Machine T11			1				1				1										
	Machine T12	5		1				1		1	0	1	1							0	1	
	Machine T13	5	1	1				1		1	1	1	1							0	1	
	Machine T14	5		1				1		1	0	1	1							0	0	
	Machine T15	5		1				1		1	0	1	0							0	0	
	Machine T16	5	1	1				1		1	1	1	1							0	1	
	Machine T17	1 + 1		0				1				0	1	0						1	0	
Milling	Machine M1	5		1				0		1	1	0	0	1						0	0	
	Machine M2	5	1	1				0		1	1	1	1	1						1	0	
	Machine M3	5		0				0		1	1	1	1	1						1	0	
	Machine M4	5		0				0		1	1	1	0	1						0		
	Machine M5	5	1	1				0		1	1	1	0	1						0		
	Machine M6	5	1	1				0		1	1	1	0	1						0		
	Machine M7	5	1	1				0		1	1	1	0	1						0		
	Machine M8	5	1	0				0		1	1	0	0	0						0	0	
	Machine M9	4 + 1	1	1				0		1	1	1	1	1						0	0	
	Machine M10	4 + 1	1	1				0		1	1	1	1	1						0	0	
	Machine M11	5	1	1				0		1	1	1	1	1						0	0	
Multitask	Machine TM1	5	1	1				1		1	1	1	1	1						1	0	
	Machine TM2	5	1	1				1		1	1	1	1	1						1	0	
	Machine TM3	5	1	1				1		1	1	1	1	1						1	0	
	Machine TM4	5	1	0				1		1	1	1	1	1						1	0	
	Machine TM5	5	1	1				1		1	1	1	1	1						1	0	
	Machine TM6	5	1					1		1	1	1	1	1						0	0	
	Machine TM7	5	1					1		1	1	1	1	1						0		
	Machine TM8	5	1	1				1		1	1	1	1	1						1	0	
	Machine TM9	5	1	1				1		1	1	1	1	1						1	0	
	Machine TM10	5	1	1				1		1	1	1	1	1						1	0	
	Machine TM11	5	1	1				1		1	1	1	1	1						1	0	

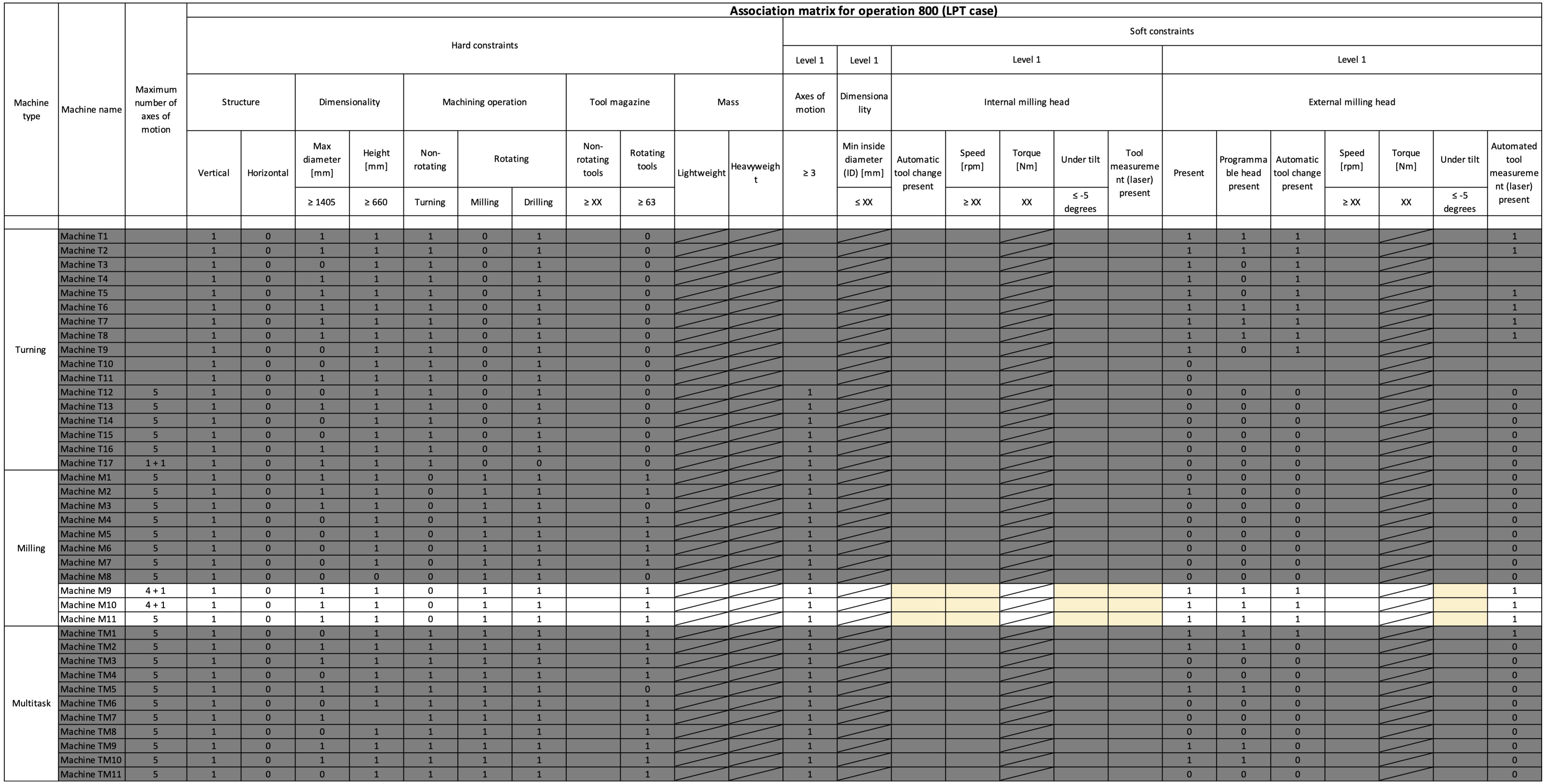
Figure 5.20: The association matrix for operation 600 (part 2)

Machine type	Machine name	Maximum number of axes of motion	Association matrix for operation 700 (LPT case)																								
			Hard constraints											Soft constraints													
														Level 1	Level 1	Level 1					Level 1						
			Structure		Dimensionality		Machining operation			Tool magazine		Mass		Axes of motion	Dimensionality	Internal milling head					External milling head						
			Vertical	Horizontal	Max diameter [mm]	Height [mm]	Non-rotating	Rotating		Non-rotating tools	Rotating tools	Lightweight	Heavyweight	≥ 3	Min inside diameter (ID) [mm]	Automatic tool change present	Speed [rpm]	Torque [Nm]	Under tilt	Tool measurement (laser) present	Present	Programmable head present	Automatic tool change present	Speed [rpm]	Torque [Nm]	Under tilt	Automated tool measurement (laser) present
					≥ 1405	≥ 660	Turning	Milling	Drilling	≥ XX	≥ 10				≤ 1330		≥ XX	XX	≤ -5 degrees					≥ XX	XX	≤ -5 degrees	
Turning	Machine T1		1	0	1	1	1	0	1		1										1	1	1				1
	Machine T2		1	0	1	1	1	0	1		1										1	1	1				1
	Machine T3		1	0	0	1	1	0	1		1										1	0	1				
	Machine T4		1	0	1	1	1	0	1		1										1	0	1				
	Machine T5		1	0	1	1	1	0	1		1										1	0	1				1
	Machine T6		1	0	1	1	1	0	1		1										1	1	1				1
	Machine T7		1	0	1	1	1	0	1		1										1	1	1				1
	Machine T8		1	0	1	1	1	0	1		1										1	1	1				1
	Machine T9		1	0	0	1	1	0	1		1										1	0	1				
	Machine T10		1	0	0	1	1	0	1		0										0						
	Machine T11		1	0	1	1	1	0	1		1										0						
	Machine T12	5	1	0	0	1	1	0	1		1			1							0	0	0				0
	Machine T13	5	1	0	1	1	1	0	1		1			1							0	0	0				0
	Machine T14	5	1	0	0	1	1	0	1		1			1							0	0	0				0
	Machine T15	5	1	0	0	1	1	0	1		1			1							0	0	0				0
	Machine T16	5	1	0	1	1	1	0	1		1			1							0	0	0				0
	Machine T17	1 + 1	1	0	1	1	1	0	0		1			1							0	0	0				0
Milling	Machine M1	5	1	0	1	1	0	1	1		1			1							0	0	0				0
	Machine M2	5	1	0	1	1	0	1	1		1			1							1	0	0				0
	Machine M3	5	1	0	1	1	0	1	1		1			1							0	0	0				0
	Machine M4	5	1	0	0	1	0	1	1		1			1							0	0	0				0
	Machine M5	5	1	0	0	1	0	1	1		1			1							0	0	0				0
	Machine M6	5	1	0	0	1	0	1	1		1			1							0	0	0				0
	Machine M7	5	1	0	0	1	0	1	1		1			1							0	0	0				0
	Machine M8	5	1	0	0	0	0	1	1		1			1							0	0	0				0
	Machine M9	4 + 1	1	0	1	1	0	1	1		1			1							1	1	1				1
	Machine M10	4 + 1	1	0	1	1	0	1	1		1			1							1	1	1				1
	Machine M11	5	1	0	1	1	0	1	1		1			1							1	1	1				1
Multitask	Machine TM1	5	1	0	0	1	1	1	1		1			1							1	1	1				1
	Machine TM2	5	1	0	1	1	1	1	1		1			1							1	1	0				0
	Machine TM3	5	1	0	1	1	1	1	1		1			1							0	0	0				0
	Machine TM4	5	1	0	0	1	1	1	1		1			1							0	0	0				0
	Machine TM5	5	1	0	1	1	1	1	1		1			1							1	1	0				0
	Machine TM6	5	1	0	0	1	1	1	1		1			1							0	0	0				0
	Machine TM7	5	1	0	1		1	1	1		1			1							0	0	0				0
	Machine TM8	5	1	0	0	1	1	1	1		1			1							0	0	0				0
	Machine TM9	5	1	0	1	1	1	1	1		1			1							1	1	0				0
	Machine TM10	5	1	0	1	1	1	1	1		1			1							1	1	0				0
	Machine TM11	5	1	0	0	1	1	1	1		1			1							0	0	0				0

Figure 5.21: The association matrix for operation 700 (part 1)

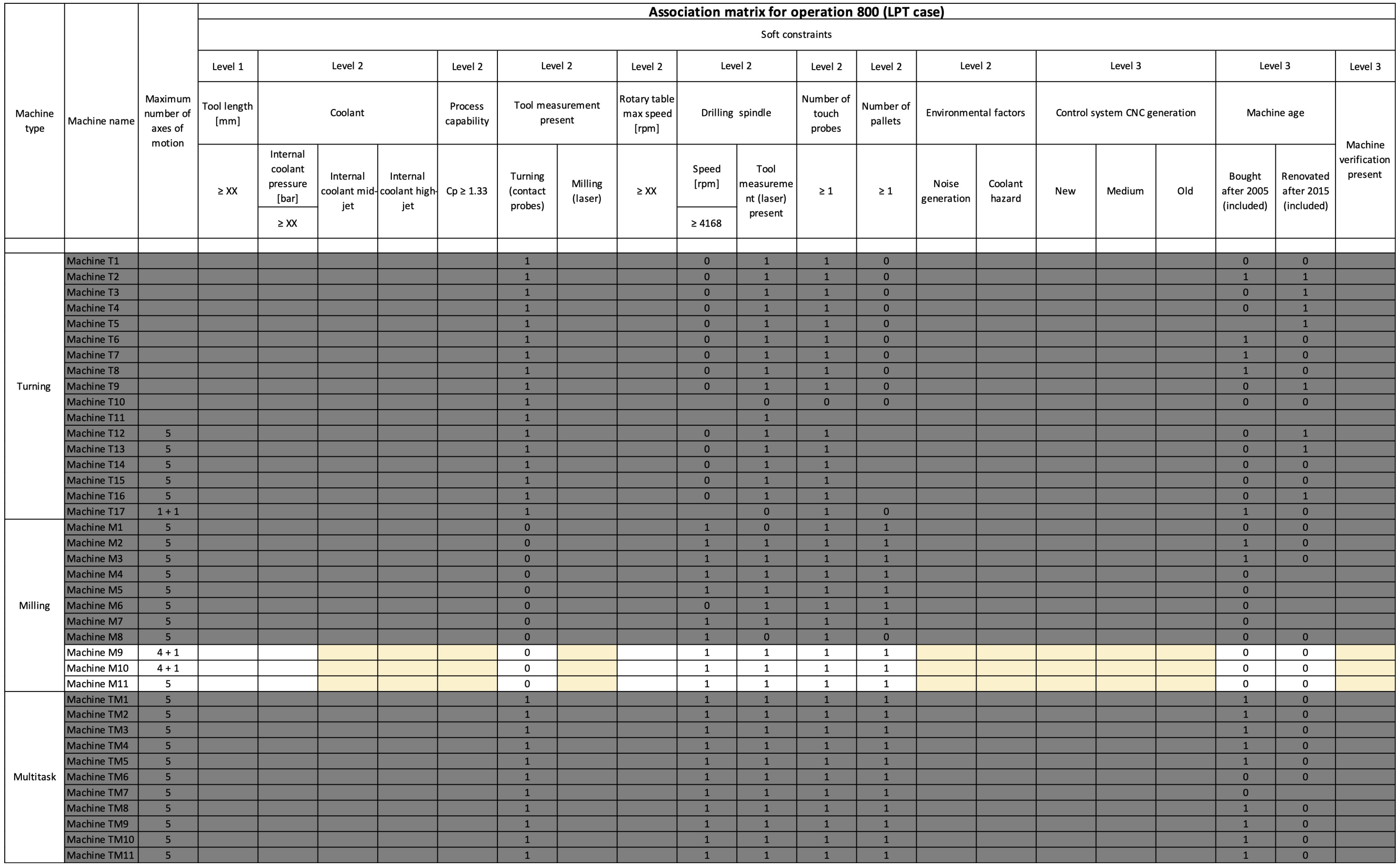
Machine type	Machine name	Maximum number of axes of motion	Association matrix for operation 700 (LPT case)																			
			Soft constraints																			
			Level 1	Level 2			Level 2	Level 2		Level 2	Level 2		Level 2	Level 2	Level 2		Level 3			Level 3		Level 3
			Tool length [mm]	Coolant			Process capability	Tool measurement present		Rotary table max speed [rpm]	Drilling spindle		Number of touch probes	Number of pallets	Environmental factors		Control system CNC generation			Machine age		Machine verification present
			≥ XX	Internal coolant pressure [bar]	Internal coolant mid-jet	Internal coolant high-jet	Cp ≥ 1.33	Turning (contact probes)	Milling (laser)	≥ XX	Speed [rpm]	Tool measurement (laser) present	≥ 1	≥ 1	Noise generation	Coolant hazard	New	Medium	Old	Bought after 2005 (included)	Renovated after 2015 (included)	
				≥ XX							≥ 885											
Turning	Machine T1							1			1	1	1	0						0	0	
	Machine T2							1			1	1	1	0						1	1	
	Machine T3							1			1	1	1	0						0	1	
	Machine T4							1			1	1	1	0						0	1	
	Machine T5							1			1	1	1	0							1	
	Machine T6							1			1	1	1	0						1	0	
	Machine T7							1			1	1	1	0						1	0	
	Machine T8							1			1	1	1	0						1	0	
	Machine T9							1			1	1	1	0						0	1	
	Machine T10							1				0	0	0						0	0	
	Machine T11							1				1										
	Machine T12	5						1			1	1	1							0	1	
	Machine T13	5						1			1	1	1							0	1	
	Machine T14	5						1			1	1	1							0	0	
	Machine T15	5						1			1	1	1							0	0	
	Machine T16	5						1			1	1	1							0	1	
	Machine T17	1 + 1						1				0	1	0						1	0	
Milling	Machine M1	5						0			1	0	1	1						0	0	
	Machine M2	5						0			1	1	1	1						1	0	
	Machine M3	5						0			1	1	1	1						1	0	
	Machine M4	5						0			1	1	1	1						0		
	Machine M5	5						0			1	1	1	1						0		
	Machine M6	5						0			1	1	1	1						0		
	Machine M7	5						0			1	1	1	1						0		
	Machine M8	5						0			1	0	1	0						0	0	
	Machine M9	4 + 1						0			1	1	1	1						0	0	
	Machine M10	4 + 1						0			1	1	1	1						0	0	
	Machine M11	5						0			1	1	1	1						0	0	
Multitask	Machine TM1	5						1			1	1	1	1						1	0	
	Machine TM2	5						1			1	1	1	1						1	0	
	Machine TM3	5						1			1	1	1	1						1	0	
	Machine TM4	5						1			1	1	1	1						1	0	
	Machine TM5	5						1			1	1	1	1						1	0	
	Machine TM6	5						1			1	1	1	1						0	0	
	Machine TM7	5						1			1	1	1	1						0		
	Machine TM8	5						1			1	1	1	1						1	0	
	Machine TM9	5						1			1	1	1	1						1	0	
	Machine TM10	5						1			1	1	1	1						1	0	
	Machine TM11	5						1			1	1	1	1						1	0	

Figure 5.22: The association matrix for operation 700 (part 2)



			Association matrix for operation 800 (LPT case)																								
			Hard constraints											Soft constraints													
														Level 1	Level 1	Level 1					Level 1						
Machine type	Machine name	Maximum number of axes of motion	Structure		Dimensionality		Machining operation			Tool magazine		Mass		Axes of motion	Dimensionality	Internal milling head					External milling head						
			Vertical	Horizontal	Max diameter [mm]	Height [mm]	Non-rotating	Rotating		Non-rotating tools	Rotating tools	Lightweight	Heavyweight	≥ 3	Min inside diameter (ID) [mm]	Automatic tool change present	Speed [rpm]	Torque [Nm]	Under tilt	Tool measurement (laser) present	Present	Programmable head present	Automatic tool change present	Speed [rpm]	Torque [Nm]	Under tilt	Automated tool measurement (laser) present
					≥ 1405	≥ 660	Turning	Milling	Drilling	≥ XX	≥ 63				≤ XX		≥ XX	XX	≤ -5 degrees					≥ XX	XX	≤ -5 degrees	
Turning	Machine T1		1	0	1	1	1	0	1		0										1	1	1				1
	Machine T2		1	0	1	1	1	0	1		0										1	1	1				1
	Machine T3		1	0	0	1	1	0	1		0										1	0	1				
	Machine T4		1	0	1	1	1	0	1		0										1	0	1				
	Machine T5		1	0	1	1	1	0	1		0										1	0	1				1
	Machine T6		1	0	1	1	1	0	1		0										1	1	1				1
	Machine T7		1	0	1	1	1	0	1		0										1	1	1				1
	Machine T8		1	0	1	1	1	0	1		0										1	1	1				1
	Machine T9		1	0	0	1	1	0	1		0										1	0	1				
	Machine T10		1	0	0	1	1	0	1		0										0						
	Machine T11		1	0	1	1	1	0	1		0										0						
	Machine T12	5	1	0	0	1	1	0	1		0			1							0	0	0				0
	Machine T13	5	1	0	1	1	1	0	1		0			1							0	0	0				0
	Machine T14	5	1	0	0	1	1	0	1		0			1							0	0	0				0
	Machine T15	5	1	0	0	1	1	0	1		0			1							0	0	0				0
	Machine T16	5	1	0	1	1	1	0	1		0			1							0	0	0				0
	Machine T17	1 + 1	1	0	1	1	1	0	0		0			1							0	0	0				0
Milling	Machine M1	5	1	0	1	1	0	1	1		1			1							0	0	0				0
	Machine M2	5	1	0	1	1	0	1	1		1			1							1	0	0				0
	Machine M3	5	1	0	1	1	0	1	1		0			1							0	0	0				0
	Machine M4	5	1	0	0	1	0	1	1		1			1							0	0	0				0
	Machine M5	5	1	0	0	1	0	1	1		1			1							0	0	0				0
	Machine M6	5	1	0	0	1	0	1	1		1			1							0	0	0				0
	Machine M7	5	1	0	0	1	0	1	1		1			1							0	0	0				0
	Machine M8	5	1	0	0	0	0	1	1		0			1							0	0	0				0
	Machine M9	4 + 1	1	0	1	1	0	1	1		1			1							1	1	1				1
	Machine M10	4 + 1	1	0	1	1	0	1	1		1			1							1	1	1				1
	Machine M11	5	1	0	1	1	0	1	1		1			1							1	1	1				1
Multitask	Machine TM1	5	1	0	0	1	1	1	1		1			1							1	1	1				1
	Machine TM2	5	1	0	1	1	1	1	1		1			1							1	1	0				0
	Machine TM3	5	1	0	1	1	1	1	1		1			1							0	0	0				0
	Machine TM4	5	1	0	0	1	1	1	1		1			1							0	0	0				0
	Machine TM5	5	1	0	1	1	1	1	1		0			1							1	1	0				0
	Machine TM6	5	1	0	0	1	1	1	1		1			1							0	0	0				0
	Machine TM7	5	1	0	1		1	1	1		1			1							0	0	0				0
	Machine TM8	5	1	0	0	1	1	1	1		1			1							0	0	0				0
	Machine TM9	5	1	0	1	1	1	1	1		1			1							1	1	0				0
	Machine TM10	5	1	0	1	1	1	1	1		1			1							1	1	0				0
	Machine TM11	5	1	0	0	1	1	1	1		1			1							0	0	0				0

Figure 5.23: The association matrix for operation 800 (part 1)



Machine type	Machine name	Maximum number of axes of motion	Association matrix for operation 800 (LPT case)																			
			Soft constraints																			
			Level 1	Level 2			Level 2	Level 2		Level 2	Level 2		Level 2	Level 2	Level 2		Level 3			Level 3		Level 3
			Tool length [mm]	Coolant			Process capability	Tool measurement present		Rotary table max speed [rpm]	Drilling spindle		Number of touch probes	Number of pallets	Environmental factors		Control system CNC generation			Machine age		Machine verification present
			≥ XX	Internal coolant pressure [bar]	Internal coolant mid-jet	Internal coolant high-jet	Cp ≥ 1.33	Turning (contact probes)	Milling (laser)	≥ XX	Speed [rpm]	Tool measurement (laser) present	≥ 1	≥ 1	Noise generation	Coolant hazard	New	Medium	Old	Bought after 2005 (included)	Renovated after 2015 (included)	
				≥ XX							≥ 4168											
Turning	Machine T1							1			0	1	1	0						0	0	
	Machine T2							1			0	1	1	0						1	1	
	Machine T3							1			0	1	1	0						0	1	
	Machine T4							1			0	1	1	0						0	1	
	Machine T5							1			0	1	1	0							1	
	Machine T6							1			0	1	1	0						1	0	
	Machine T7							1			0	1	1	0						1	0	
	Machine T8							1			0	1	1	0						1	0	
	Machine T9							1			0	1	1	0						0	1	
	Machine T10							1				0	0	0						0	0	
	Machine T11							1				1										
	Machine T12	5						1			0	1	1							0	1	
	Machine T13	5						1			0	1	1							0	1	
	Machine T14	5						1			0	1	1							0	0	
	Machine T15	5						1			0	1	1							0	0	
	Machine T16	5						1			0	1	1							0	1	
	Machine T17	1 + 1						1				0	1	0						1	0	
Milling	Machine M1	5						0			1	0	1	1						0	0	
	Machine M2	5						0			1	1	1	1						1	0	
	Machine M3	5						0			1	1	1	1						1	0	
	Machine M4	5						0			1	1	1	1						0		
	Machine M5	5						0			1	1	1	1						0		
	Machine M6	5						0			0	1	1	1						0		
	Machine M7	5						0			1	1	1	1						0		
	Machine M8	5						0			1	0	1	0						0	0	
	Machine M9	4 + 1						0			1	1	1	1						0	0	
	Machine M10	4 + 1						0			1	1	1	1						0	0	
	Machine M11	5						0			1	1	1	1						0	0	
Multitask	Machine TM1	5						1			1	1	1	1						1	0	
	Machine TM2	5						1			1	1	1	1						1	0	
	Machine TM3	5						1			1	1	1	1						1	0	
	Machine TM4	5						1			1	1	1	1						1	0	
	Machine TM5	5						1			1	1	1	1						1	0	
	Machine TM6	5						1			1	1	1	1						0	0	
	Machine TM7	5						1			1	1	1	1						0		
	Machine TM8	5						1			1	1	1	1						1	0	
	Machine TM9	5						1			1	1	1	1						1	0	
	Machine TM10	5						1			1	1	1	1						1	0	
	Machine TM11	5						1			1	1	1	1						1	0	

Figure 5.24: The association matrix for operation 800 (part 2)

5.7 Obtaining a single association matrix for each product

Sometimes, instead of a single operation, it may be interesting and useful to obtain an association matrix for the whole product, thus not dividing it into association matrices for each operation. One reason for doing this would be to be able to include a certain product in a specific product flow. In this case, one more step than Section 5.6 needs to be carried out, grouping all the operations that make up a whole product and checking for compatibility between them. The prerogative of this procedure is to assess whether all the operations that make up a product can be carried out on one or as few machines as possible. Of course, to avoid capacity problems, the capacity of the machine in the value stream must be taken into account when allocating a specific resource in practice. Table 5.8 and Table 5.9 show the resource allocations for the TEC and LPT case (considered as products as a whole) respectively. Both operations 1600 and 1700 for the TEC can be performed on one of the machines indicated in Table 5.8. The same does not apply to the LPT case, whose operations (500, 600, 700, 800) must be performed on at least two different machines among those listed in Table 5.9.

Table 5.8: Machines qualified for the TEC (considered as a product as a whole)

Machine type	Machine name
Multitask	Machine TM2
Multitask	Machine TM5
Multitask	Machine TM9
Multitask	Machine TM10

Table 5.9: Machines qualified for the LPT case (considered as a product as a whole)

Operation	Machine type	Machine name
Operations 500 and 600	Multitask	Machine TM2
Operations 500 and 600	Multitask	Machine TM3
Operations 500 and 600	Multitask	Machine TM5
Operations 500 and 600	Multitask	Machine TM7
Operations 500 and 600	Multitask	Machine TM9
Operations 500 and 600	Multitask	Machine TM10
Operations 700 and 800	Milling	Machine M9
Operations 700 and 800	Milling	Machine M10
Operations 700 and 800	Milling	Machine M11

5.8 Selection of the optimal machine

One of GKN Aerospace requirements was to provide some input on identifying an optimal machine (or as few optimal machines as possible) suitable to manufacture a set of products, e.g., the TEC, LPT case and ICC together. In this case, the starting point is what has been shown in Section 5.7. The procedure involves grouping all the operations of a specified number of products in just one association matrix. For example, Table 5.10 shows the optimal machines to select from when it comes to manufacturing both the TEC and LPT case together. In this case, the minimum number of optimal machines is two, one to be selected from the multitask machines (TM2, TM5, TM9 and TM10) and the other to be selected from the milling machines (M9, M10, M11).

Table 5.10: Machines qualified for the LPT case (considered as a product as a whole)

Optimal machine	**Machine type**	**Machine name**
Optimal machine 1	Multitask	Machine TM2
Optimal machine 1	Multitask	Machine TM5
Optimal machine 1	Multitask	Machine TM9
Optimal machine 1	Multitask	Machine TM10
Optimal machine 2	Milling	Machine M9
Optimal machine 2	Milling	Machine M10
Optimal machine 2	Milling	Machine M11

6

Discussion

In this chapter, the results are reviewed and discussed. Recommendations to make the developed model more efficient and responsive are further proposed.

6.1 Answering the research questions (RQs)

This section covers the answers to the three research questions (RQs) presented in the "Introduction" chapter.

6.1.1 RQ1

What are the factors that control the assignment of a product to a machine? How is it determined that a machine is technically capable of performing a certain operation?

The first RQ concerns the parameters that make up the two dimensions of this study, i.e., KPFs (and their required machining operations) and KMCs. The first part of the RQ1 was answered by identifying the factors that directly relate to the KPFs, and specifically to their operations (made of one or several job types). These factors are presented in the operations table, divided into two sub-tables based on their physical nature, i.e., threshold sub-table (Table 6.1) and 1/0 sub-table (Table 6.2). The first sub-table contains factors that cannot be expressed by means of the binary approach (which implies only 1 and 0 values). For the threshold sub-table, numbers other than 1 and 0 were specified. Thereafter, based on these values, threshold values for each operation were identified in a separate table (at the bottom of Figure 5.6). These threshold values were used then to set the limits for each operation in the association matrix. The 1/0 sub-table contains parameters that can be expressed with only 1 and 0 values, where 1 indicates a positive response and 0 indicates a negative response. Both sub-tables indicate the requirements for each KPF in a comprehensive way, thus helping to establish the allocation of a certain KPF to a given machine(s).

Table 6.1: Factors from the threshold sub-table

Factor	**Detail**
Dimensionality	Max diameter Min Inside Diameter (ID) Max height
Tool magazine size	Number of non-rotating tools Number of non-rotating tools Number of touch probes
Number of axes of motion	-
Internal milling head	Speed Torque
External milling head	Speed Torque
Internal coolant pressure	-
Tool length	-
Rotary table max speed	-
Drilling spindle speed	-

Table 6.2: Factors from the 1/0 sub-table

Factor	**Detail**
Machine structure	Vertical Horizontal
Machining operation	Non-rotating (turning) Rotating (milling and drilling)
Internal milling head	Automatic tool change Under tilt Tool measurement (laser)
External milling head	Present Programmable head Automatic tool change Under tilt Automated tool measurement (laser)
Coolant	Internal coolant Internal coolant mid-jet Internal coolant high-jet
Drilling spindle	Tool measurement (laser)

The second part of the RQ1 was addressed by identifying the parameters that relate to machines and their capabilities. These parameters are presented in Table 6.3. Unlike the operations table, for the KMCs table it was not necessary to specify values other than 1 and 0. Therefore, compared to the operations table, the KMCs table resulted in a simplified binary approach, where 1 indicates a positive response and 0 indicates a negative response. Based on the resulting 1 and 0 values, it was possible to identify the machines technically capable of performing a certain job type (or operation) on a given KPF.

Table 6.3: Factors that relate to machines and their capabilities

Factor	**Detail**
Machine structure	Vertical Horizontal
Dimensionality	Max diameter Min Inside Diameter (ID) Height
Machining operation	Non-rotating (turning) Rotating (milling and drilling)
Tool magazine size	Non-rotating tools Rotating tools
Mass	Lightweight Heavyweight
Axes of motion	-
Internal milling head	Automatic tool change Speed Torque Under tilt Tool measurement (laser)
External milling head	Programmable head Automatic tool change Speed Torque Under tilt Automated tool measurement
Maximum tool length	-
Coolant	Internal coolant pressure Internal coolant mid-jet Internal coolant high-jet
Process capability (Cp)	-
Tool measurement	Turning (contact probes) Milling (laser)
Rotary table max speed	-
Drilling spindle	Speed Tool measurement (laser)
Number of touch probes	-
Number of pallets	-
Environmental factors	Noise generation Coolant hazard
CNC generation	New Medium Old
Machine age	Bought after 2005 (included) Renovated after 2015 (included)
Machine verification	-

6.1.2 RQ2

How should the most appropriate machines (with respect to optimized resource allocation) be selected to perform a certain operation on a given product?

The selection of the suitable machine(s) to perform a certain job type (or operation) on a given KPF was obtained by associating the two dimensions of the study, i.e., KPFs and KMCs. The procedure to determine the machine(s) suitable to perform a specific job type (or operation) on a given KPF develops on three levels of qualification, as discussed in Section 5.5. The first level, which ensures that the indispensable requirements are met, aims at selecting the machine(s) according to the hard constraints of the KMCs discussed in Section 5.2. By applying this first filter to the model, a certain number of machines that do not meet the requirements set by the hard constraints is discarded from the machine list. An additional filter is applied including the soft constraints of the KMCs discussed in Section 5.2. This procedure excludes further machines from the machine list, keeping only the machines that comply with the three levels of soft constraints. This results in the selection of the machine(s) that not only meets the mandatory constraints (hard constraints), but also guarantees superior quality and reduced production costs.

6.1.3 RQ3

What additional technical information needs to be evaluated to carry out the allocations?

The third RQ was answered by adding a further level of qualification to the procedure to select optimal resource allocations. From a chronological perspective, this additional information should be understood as a continuation on a further level of analysis of the procedure for selecting the appropriate machine(s) discussed in RQ2. This additional level of qualification (presented in Section 5.5.1) is excluded from the main method due to incompatibilities, i.e., issues encountered when integrating it to the binary approach of the main method (based on the 1 and 0 values). The parameters excluded from the main approach are the tool interface system, machine operator skills and rotation axes layout. Therefore, even after the previous two qualification levels (hard and soft constraints) are completed, it might be useful to check for these additional parameters. For example, the tool interface system of the machine should be carefully evaluated, as it directly affects the shifting of a job type from a machine to another. Moreover, certain machines can be managed only by skilled operators, hence it is necessary to check if there are operators who are available to run the machines that are selected at the end of the qualification procedure. Therefore, in some cases such other technical information need also to be considered before finalizing the allocation process. The parameters part of this additional level of qualification ensures even more comprehensive and optimized resource allocations than the level of qualification discussed for RQ2.

6.2 Limitations to the developed approach

Although the developed procedure to qualify machines is reasonably comprehensive and reliable, it still has some limitations, which are discussed in the next sections.

6.2.1 Data gathering

One of the main limitations to the approach, which prevents from obtaining reliable results, relates to the availability of data on which to base the model. Since the approach is highly sensitive and reliant on data, in order to obtain solid results, a huge amount of data is required. This might open up to data gathering problems, which were actually encountered during the project, and which might have a direct negative effect on the results of the model.

The two examples given in Section 5.6 served as tests to verify the applicability of the developed approach to real cases. However, it is important to point out that the same data could not be retrieved for both examples. For the LPT case, most of the data was retrieved for each specific KPF. For the TEC, instead, the data retrieved was on the operations level. As a result, for the LPT case a specific KPF could prevent moving a job type to a machine; for the TEC an entire operation could prevent moving the operation to a machine. This is a rather significant difference between the two examples, which is discussed in more detail in the next section.

6.2.2 Complexity levels

Different levels of detail can be chosen when it comes to evaluating resource allocation. In some cases, it may be useful to determine the machine allocations for a product as a whole, as it has been shown in Section 5.7. However, this level of complexity identifies general allocations not based on each job type, thus leaving apart a huge amount of information, which could be used to optimize the resource allocation results. The next level of detail would be to assess each operation, meant to be a set of one or more job types performed on one or more KPFs. This is the complexity level adopted for this study. An intermediate level of detail would be to consider each KPF individually, analyzing the association between the machines with each job type. Consequently, the level of complexity of the model increases, but on the other hand, more information and details can be used to allocate resources. A further level of detail would involve the division of each machining operation performed on each KPF. For example, if a flange is taken as an example, the machining operations performed on the flat, lateral and bottom surface, divided into turning, milling and drilling operations all need to be assessed individually. This level of detail, of course, exponentially increases the degree of complexity of the model.

6.2.3 Inheriting process

The “inheriting” process has been presented in Section 5.6 as a solution to bridge the gap of missing data that prevented the model from running for the two example products, i.e., the TEC and LPT case. Although this procedure made it possible to run the model with reasonable reliability, it is far from being considered and accepted as a rigorous scientific approach. The risks involved in proceeding this way are several and may negatively influence the final results. For instance, a risk when inheriting information from a well-known machine to determine certain data of a similar machine may be that the parameters derived through this inheriting procedure do not contain specific information, e.g., when deriving information for a machine that has a ceramic end mill capability from a similar machine that does not have a ceramic end mill capability but just a tungsten carbide capability. As a consequence, part of the information is lost while using this approach. Nevertheless, for the purpose of this study (which is mainly to develop the association model), the benefits of using this procedure outweigh the risks, as the method makes it possible to test the model with a reasonably reliable and acceptable accuracy.

6.3 Comparison of the allocations from the developed approach with the current allocations at GKN Aerospace

One of the reasons to run the model for the two products TEC and LPT case was to be able to compare the results from the model developed through this study with the current allocations at GKN Aerospace.

6.3.1 TEC

The machines selected through the model for operation 1600 are shown in Table 6.4, along with the current allocations for the same operation. The comparison shows that there are no machines in common, since the model developed in this study qualifies only multitask machines and the current allocations are all turning machines. The KMC that had a major impact on such a result was the soft constraint checking for the number of pallets available. For this capability, a threshold value of one pallet was set, resulting in excluding almost all turning machines (from T1 to T10). It is, perhaps, a too strict value that GKN Aerospace may think of excluding from a real case, as it severely affects the resulting final allocations. However, in the specific case of operation 1600, the KMC that directly affected the exclusion of machines T12 and T13 (current allocations) was the external milling head, which is a requirement from the operations table (Figure 5.10), and whose required capability is not present in both the machines (Figure 5.11).

Table 6.4: Machines selected vs. current allocations for operation 1600

Machines selected	**Current allocations**
TM2	T12
TM5	T13
TM9	
TM10	

The machines selected through the model for operation 1700 are shown in Table 6.5, along with the current allocations for the same operation. In the case of operation 1700, the comparison shows that the model qualifies the same machines that are currently allocated, plus it qualifies two more machines (TM1 and TM2).

Table 6.5: Machines selected vs. current allocations for operation 1700

Machines selected	**Current allocations**
TM1	
TM2	
TM5	TM5
TM9	TM9
TM10	TM10

6.3.2 LPT case

The machines selected through the model for operation 500 are shown in Table 6.6, along with the current allocations for the same operation. The comparison shows that there are no machines in common, since the model developed in this study qualifies only multitask machines and the current allocations are all turning machines. One of the reasons for the exclusion of the T1, T6 and T10 machines is their lack of milling capability, indicated as a hard constraint in the operations table shown in Figure 5.16. A further reason to exclude machine T10 concerns the dimensionality parameter, i.e., the machine has an internal space (in terms of max diameter) that does not allow the product to fit into the machine.

Table 6.6: Machines selected vs. current allocations for operation 500

Machines selected	**Current allocations**
TM2	T1
TM3	T6
TM5	T10
TM7	
TM9	
TM10	

For operation 600, the machines shown in Table 6.7 were qualified, along with the current allocations. Operation 600 presents the same reasons for excluding the machines described for operation 500.

Table 6.7: Machines selected vs. current allocations for operation 600

Machines selected	Current allocations
TM2	T1
TM3	T6
TM5	T10
TM7	
TM9	
TM10	

The machines selected through the model for operation 700 are shown in Table 6.8, along with the current allocations for the same operation. The comparison shows that there are no machines in common, even if the machines from both sides are all milling machines. The reason for excluding machine M1 from the model is the lack of the external milling head capability. Machine M2 has the external milling head capability, but the reason for excluding it is that it does not have the automatic tool change for that milling capability, required by Figure 5.16.

Table 6.8: Machines selected vs. current allocations for operation 700

Machines selected	Current allocations
M9	M1
M10	M2
M11	

For operation 800, the machines shown in Table 6.9 were qualified, along with the current allocations. As for operation 700, the comparison between the machines qualified through the method and the current allocations shows that there are no machines in common, even if the machines from both sides are all milling machines. The reason for excluding machine M1 from the model is again the lack of the external milling head capability, required by the operations table in Figure 5.16. In this case, the reason for excluding machine M2 is the lack of programmable external milling head capability, indicated as a requirement in Figure 5.16.

Table 6.9: Machines selected vs. current allocations for operation 800

Machines selected	Current allocations
M9	M1
M10	M2
M11	

6.4 What machine to choose in the end?

As discussed in the previous section, some constraints could have a severe impact on the outcome of the model, even if they are categorized as soft constraints. For instance, from the two examples in Sections 5.6.1 and 5.6.2, the number of pallets and the external milling head capabilities heavily affect the final qualification of machines. Therefore, it is crucial to make specific decisions whether to consider or not some of the capabilities while allocating resources. In other words, when applying this model to real cases, it is up to the company to choose the filter that it considers appropriate to apply. For instance, the number of pallets could be considered by GKN Aerospace as a non-critical capability, and therefore not applicable to the model. This would result in an increased number of available machines to be allocated.

Another decision dilemma could arise if a machine has most of the KMCs required by an operation but does not meet just one or a few of them. For example, for a certain number of KPFs (part of a certain operation), a speed of 2000 rpm for the external milling head is required and met by the machine(s) qualified, but for just one KPF a speed of 6000 rpm is required and not met by the machine(s) previously qualified. In this case, a decision must be made about keeping the machine(s) qualified for a speed of 2000 rpm and trying to machine all the KPFs (included in the given operation) with an acceptable result (if possible), or evaluating the investment of buying a new machine that meets all the specifications required. Another solution may be to shift from a machine type (milling, turning, multitask) to another machine type that instead satisfies the requirements that were lacking on the previous machine. For example, if possible, an option could be to shift a job type from a milling machine to a turning machine that meets the KMCs requirements. However, it is important to carefully evaluate whether the output is acceptable or not because sometimes shifting from e.g., a milling to a turning machine affects the quality of the product.

The same applies when it comes to machine a new product or a new set of products, not present in the current production flow. The corresponding required KMCs to perform the operations on the new product can be synthesized using this approach. If none of the existing machines satisfy the requirements, the possibilities are either modify the closest existing machine with that combination of KMCs, e.g., by adding the KMCs that are missing, or buy a new machine that has all the required KMCs. Of course, the adoption of one or the other choice largely depends on the specific case. This evaluation is not part of this study but can be seen as further research to be developed.

6.5 Sustainability

Sustainability entirely permeates this study, as the proposed model aims at optimizing resource allocation, thereby eliminating, or at least reducing, underutilization or misallocation of resources that could lead to waste, rework or other negative effects on sustainability. From the perspective of the Triple Bottom Line (TBL), the sustainability implications of this study cover the environmental and economic dimensions (Lewis & Slack, 2017). The main purpose of the developed model is to ensure optimal resource allocations, leading to fully utilized resources, high-quality outputs, cost reduction, eventually reducing any form of waste (e.g., scrap rate, rework, etc.). Moreover, by effectively matching machine capabilities and product features to find optimal resource allocations, machines' underutilization and capacity problems (for example long queues for the most capable machines) can be avoided. On the economic sustainability perspective, the developed approach ensures cost reduction for the same reasons discussed above since e.g., reworked and scrapped products lead to higher costs and unnecessary energy consumption that could be easily avoided by adopting the approach proposed in this study (Storck, 2012).

6.6 Recommendations

This section covers the recommendations given to make the model developed through this project more efficient, reactive and easier to apply to real cases.

6.6.1 Automatic management of the model

In order to make the approach applicable to real cases, the compilation of both the KMCs and operations tables first, and the association matrices then should be automated through programming, e.g., MATLAB or similar software. Although the model has been applied to just two products (TEC and LPT case) in this study, the manual procedure to fill in the data into the tables and matrices resulted to be complex, time consuming (not acceptable for a quick-decision environment of a real company) and prone to human mistakes. Moreover, the method does not show its full potential (mainly for the selection of the optimal machine presented in Section 5.8) with only two products, but it is necessary to extend the study to several different products at the same time. Evidently, for this to be done an automation of the approach is required. Therefore, this approach could be carried out automatically in the future. For instance, the user could interact with a simplified interface (not the tables and matrices shown in this study) where to enter the required hard and soft constraints. With the computing power of the software, it instantly and automatically displays the qualified machines. In addition, a standardization of the data collection should be implemented too. This aspect is described in more detail in the next two sections.

6.6.2 Tagging/labelling of KPFs

An effective way to standardize the gathering process of the data relating to each KPF concerns the tagging (or labelling) of the KPFs and the storing of this data in a database organized according to a standardized structure. One way to do this is to organize the KPFs into the CAD model, so that each KPF is categorized into its product type (e.g., bosses) and then each specific KPF within that category is named following a standardized procedure (e.g., bosses_inspection). Therefore, when a KPF is identified, a tag is used to categorize it and the same tag can be used for similar KPFs. This ensures a standardization and uniformity of the KPFs' names and a quick categorization for other KPFs that share similar characteristics (so that they can be included in the same category) with a KPF already present in the database. Having this categorization organized according to the same standardized names, it is then possible to check the requirements for one KPF individually, e.g., it is possible to check what is the maximum drilling speed required for only the bosses for inspection. This ensures a very detailed analysis of each KPF and quick data retrieval is obtained. However, the effort to implement such a standardized approach is huge, and it requires that all the company's departments work in parallel and aligned to the same standardized procedure, aiming to rename all existing KPFs to the new standard. In some cases, adopting a commonly accepted standard to name the KPFs into the CAD model is not enough. Even better results could be achieved by adopting a shared standard among all the company's sites across the world to work with the same parameters, thus reducing incompatibility problems related to the lack of a shared standard.

When it comes to standardizing, it is recommended to use widely accepted standards, and ISO standards (to standardize both KPFs and tools) are preferred. For instance, when it is needed to standardize data on cutting tools and toolholders, the international technical standard ISO 13399 is advised. Or else, the MTConnect standard (ANSI/MTC1.4-2018) can be used to structure and categorize with a standardized vocabulary system the manufacturing equipment, e.g., the axes of motion of all the machines in the factory can be named in the same way despite the machine manufacturer (MTConnect, 2021).

6.6.3 Automatic Feature Recognition (AFR)

One of the main limitations to the introduction of new products in the factory in a quick and optimized way is the lack of standardization of data gathering on KPFs. Considerable effort was required to only partially retrieve the KPFs data needed to run the model for the TEC and LPT case (Section 5.6.1 and Section 5.6.2). Moreover, the time required to manually retrieve this data can be considered as a limit to the applicability of the model to real cases. Therefore, in order to quickly create and update the database containing all the required data to be used to run the model, automation of data collection is required. Automatic Feature Recognition (AFR) helps to automatically identify the KPFs and extract geometrical and topological data from them (Al-wswasi & Ivanov, 2019). Not only do AFR tools help to automatically identify the KPFs, but they also implement a shared standard to store this data. In fact, the lack of standardized information formats represents a limitation to the establishment of a standardized and integrated production system, as it prevents the data from flowing smoothly through the factory's departments. Therefore, data exchange standards (such as STEP, QIF, JSON, etc.) need to be associated with the adoption of AFR tools.

The main limitation of AFR tools is that sometimes it is not possible to automatically recognize some KPFs. In such events, the smart interactive AFR (SI-AFR), which is an updated version of the AFR, can be implemented as it helps identify (by means of interactive feature recognition tools) the KPFs that have not been automatically recognized with the AFR.

7

Conclusion

This chapter is a summary of the most relevant parts of the study and a recap of the essential steps to consider when it comes to introduce new products into an existing production system.

The developed approach presented in the “Results” chapter provides an answer to all RQs by first assessing both the given products and machines for identifying the critical parameters that have a direct effect on resource allocation; thereafter, the study proceeds analyzing the relationship between products and machines (specifically, product features and machine capabilities) to develop effective resource allocation strategies. It can be concluded that all these parameters need to be carefully evaluated to ensure that the developed model works in a solid way.

The essential steps to consider when it comes to introduce new products into an existing production system, or when the specifications of currently produced products need to be updated, are:

- Identify the Key Product Features (KPFs) of the product to be introduced, analyze its similarities with the products currently produced and, based on this, include it in a specific value stream, where established knowledge and routines for the same types of products are already in place.
- Identify the Key Machine Capabilities (KMCs) required to perform the machining operations on the identified KPFs of the new product.
- Associate the KPFs and KMCs dimensions to identify effective resource allocation plans through the developed model.
- After the association of the two dimensions of this study, a criterion that must necessarily be met is the capacity availability in the value stream. If the value stream has enough capacity, it can accept the new product. To base this decision, an estimate of machine utilization is needed. Anyhow, this assessment is not part of this study.
- After introducing the new product into the value stream, an operation list is developed to identify which job types need to be performed and in which order.
- The production of the new product can start.

In conclusion, the developed model is decisive for developing resource allocation strategies when it comes to introducing new products into the current production system or when the specifications of currently produced products change. The structure of the model consists of three levels of qualification:

- The hard constraints guarantee that the machines to be allocated to a specific product are compatible and suitable to perform certain job types.
- The soft constraints ensure an enhanced output in terms of quality and cost.
- Additional factors can be taken into consideration to allocate resources, such as the tool interface system, operator skills and rotation axes layout.

This layered structure allows to choose the degree of complexity, and consequently the degree of detail, to be obtained from the method.

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