Master's Thesis

Implementation of a set of Key Performance Indicators for Manufacturing Companies by using data coming from PLM and MES systems

A Thesis in the Field of Manufacturing Operations Management for the Degree of Master of Management Engineering

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ABSTRACT

In the era of industry 4.0, manufacturing systems are evolving and becoming more intelligent than ever. The inclusion of game changing technologies, such as machine learning, big data, and Internet of Things, in manufacturing have led to multifold increase in product data. At one end, this increase in information is beneficial for product development since important insights about the design, quality and production of a product can be collected during its lifecycle, but on the other end, converting these important insights into Key Performance Indicators (KPIs) for the manufacturing plant becomes a challenging task.

The objective of this thesis is to use the information collected through different information systems of a company, e.g., PLM and MES, to compute a set of KPIs useful to analyze the behavior of the production system. The approach includes the use of ISO 22400 standard for mapping an analogy between its elements and data of Knowledge Based System. This approach has been exploited in an Italian car prototyping company.

ACKNOWLEDGEMENT

Although with the completion of this thesis, my master's degree comes to end but I hope this lifelong journey of wisdom and knowledge never ends. I am highly indebted to Department of Management and Production Engineering (DIGEP) at Politecnico Di Torino for providing me with an opportunity to pursue my dreams and polish my managerial and analytical skills. Being a part of multicultural university has been a phenomenal experience for me. During my stay at Polito, I came to know some of the most talented and exceptional individuals.

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Finally, I express my profound gratitude towards my parents and siblings who have been a vital part of my life and supported me through thick and thin. I specially dedicate this piece of work to them.

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LIST OF ACRONYMS

CAD	Computer aided design
CAPP	Computer Aided Process Planning
CIM	Computer Integrated Manufacturing
CPS	Cyber Physical Systems
DCS	Distributed Control Systems
EAI	Enterprise Application Integration
ERP	Enterprise Resource Planning
FP7	Framewo
GUI	Graphical User Interface
ICT	Information Communication Technology
IoT	Internet of Things
ISO	International Organization for Standardization
HOME	Hierarchical Open Manufacturing Europe
KBS	Knowledge Based System
MES	Manufacturing Execution System
MOM	Manufacturing Operations Management

MRP	Material Resource Planning
OESI	Outright Enterprise System Integration
PDM	Product Data Management
PLC	Programmable Logic Controller
PLM	Product Lifecycle Management
RP	Rapid Prototyping
SCM	Supply Chain Management

1. INTRODUCTION:

1.1 History OF Manufacturing Systems

In early 1980s, concept of Computer Integrated Manufacturing (CIM) was devised in which unified systems were developed by integrating standalone systems. The idea behind CIM was to provide manifold benefits like improved operational efficiency, increased flexibility, enhanced product quality, faster time to market, and fast response to changing customer needs. However, despite promising benefits, due to poor implementation of above technology, firms were unable to achieve the desired results. Nevertheless, breakthroughs in microprocessor technology, the beginning of internet era, improved computer architectures, standardization of software interfaces and acceptance of standardized software design and development techniques enabled the integration of diverse software[1].

CAD-based technologies enabled rapid prototyping[2] which proved game changer for the manufacturing industry. RP technology could produce the components directly from the CAD model bringing new perspectives in the manufacturing industry. As a result, benefits like reduction in hardware prototyping costs and short time to market was observed. Moreover, PDM/PLM system was developed to carry out a variety of tasks ranging from data management, workflow, lifecycle management to product structure and design. The main idea behind there development was to seed up the process of disturbing engineering information, while enabling the centralization of control for collaborative product development for supply eco system.

The notion behind manufacturing control started in 1950s when pneumatic controllers coupled with full graphic panel boards were used to automate the process. Later, as the technology matured, minicomputers and electronic instrumentation were prevalent for industrial control. With high replacement cost associated with complex relay-based control system, PLC (Programmable Logic Controllers) were invented. PLC technology came with liberty of programming the controllers without changing the actual hardware configuration. Initially PLC were cable of operating on a single loop with less dynamism. Moreover, when PLC offered data communication capabilities with computer peripherals, this added a whole era of flexibility to manufacturing. In mid 90s, the issue of lack of dynamism was solved when on-line measurement were incorporated in the control systems and model based multivariate controllers were installed [1]. From the twenty first century, the realization of wireless communication between devices has been made possible. With the help of internet of things and big data, we are transcending towards the digital age where sky is the limit.

1.1 Manufacturing Knowledge:

Whether an enterprise is operating in a pharmaceutical industry or automobile industry, when it comes to the manufacturing of products, there is always a connectivity of different machines or equipment and agents. During this production phase, a lot of sensors and smart instrumentation interact with each other to carry out the production. As a result, large amount of data is generated, which needs to be analyzed, cleaned, and rectified. As already mentioned, this data acts as manufacturing knowledge because a lot of critical insights can be derived from such data. For instance, in an automobile assembly line, many operations are interlocked with each other, when acting as the input of the other. If there is a defect in the fitting of doors on the car body, then it can be very analyzed by checking the history of parameters that were used to fit the doors in the car body. It is on the organization, how they deal with such precious data. It might be a problem with the design engineering department, they might have come up with wrong dimensions of the door. Whatever might be the cause, it can always be rectified by having a closer and analytical look on the data.

Another major issue concerning the production or manufacturing of the products is tacit knowledge. In some small medium enterprises, manufacturing knowledge is only confined in the minds of the operator. There is an absence of standard operating procedures and knowledge system where such data can be standardized or archived. Consequently, such organizations have difficult times to sustain their businesses in the long run. For instance, at shop floor, machine operators are very skilled in machining and fabrication of items. But all this knowledge resides in their minds, and there is no specific management system, that is recording and archiving the history of the machine data. As a result, whenever such operator leaves the company, such tacit knowledge goes with him and company has challenges dealing with the production of parts that have already been made by the company in the past. So, there is a need for formalization and standardization of knowledge generated within the industry. This leads us to define the information systems used in our data mode:

1.1.1 Manufacturing Execution System:

Manufacturing execution system (MES) is an information system that monitors, controls, and connects complex manufacturing systems with the aim of improving efficiency of production and increasing production output. MES achieves this goal by real time tracking of data during the whole product lifecycle from product release to product delivery. AMR research, who defined MES as a dynamic information system first coined the term in 1992. In modern age, the main functions of MES are following:

- Data collection
- Performance Analysis
- Staff and resource management
- Scheduling
- Document Management
- Process Management

While the benefits of MES are multifold, first we would like to dive deeper into its functioning. MES acts as bridge between controlling systems (PLCs, DCS, sensors) and planning systems (ERP, MRP) and uses the manufacturing data (resources and orders) to efficiently carry out the manufacturing processes. Data heterogeneity, which is also discussed in later chapters is the biggest issue of tailor-made shop floors. Since such shop floors locally store the production data in spreadsheets and local databases, data consolidation and software maintenance becomes a big problem[3]. The concept behind making MES was to integrate multiple point systems available in a manufacturing environment and consolidating various production execution functions under the same package. Currently, in modern world MES is being transformed into next generation execution system by involving the concepts of industry 4.0. This paradigm offers smart factories capabilities where equipment and machines can communicate wirelessly by advance ICT technologies. Moreover, with the help of advanced automation tools and internet of things, there is a lot of room for process improvement as well. Future factories will leverage technologies coupled with the functions of MES to provide advanced digitization in manufacturing environment.

1.3 Product Lifecycle Management:

Product lifecycle management is a broad concept encompassing and managing all data related to the design, production, support, and ultimate disposal of manufactured goods. The concept of PLM was first introduced in the industries where safety and control were of empirical importance such as aerospace, medical device, military, and nuclear industries. Since such industries are based on high tech and sophisticated products and outputs, a solid framework for the development and production of products was needed.

Figure 1: Product Lifecycle Management

As apparent with the definition, nowadays PLM is an intrinsic part of the manufacturing space. Like MES, Product Lifecycle Management also has multifold benefits for designing and manufacturing companies. By adopting PLM systems, firms can attain various benefits such as increasing the speed to market of new products, improving the response to market demands, delivering more new products in a shorter time, reducing product development project costs, and reducing material and energy consumption costs.

The real purpose of introducing PLM was to help engineers to collaborate, work and communicate their product design and specification across the whole life cycle of the product. Especially it was consistent for those products which needed numerous iterations during their design and engineering phase. Since changes in product and process design of later stages of product and project management are very costly and take a lot of time.

1.4 ERP:

The ERP system can be defined as an integrated cross-functional software that reengineers manufacturing, allocation, finance, human resources, and other basic business processes of a company to support its efficiency, speed, and profitability [5]. ERP helps organizations to run their day-to-day business activities by providing a central system that can be accessed by all the departments. Many ERP software applications are important to companies because they help them implement resource planning by integrating all the processes needed to run their companies with a single system[1]. Moreover, it also serves as a common platform for the concerned functions for communication, information sharing and workflow management.

ERP has evolved from a mere simple resource planning software to a powerful software incorporating all the functions including the organization. Without an ERP system, each function would optimize and structure its tasks for its own purpose, but with ERP systems, all departments of the company interact with each other and create a synergy. Furthermore, the structure of ERP system depends mostly on the company's strategic objectives. Therefore, it is not necessary the ERP system will always increase the efficiency of the enterprise. Generally, there are three types of ERP software existing in today's world: Cloud based ERP, Traditional ERP, and web-based ERP.

Cloud based ERP is based on a service provider company that gives services to its remote clients. In this way there is no need to install the serves and software at the client's location. Cloud based ERP is further divided into Infrastructure as a Service (IaaS), Platform as a service (PaaS), and software as a service (SaaS). In IaaS, this type of ERP provides, application, database, security and run time to the client whereas hardware part is controlled by the service provider. PaaS is an extension of IaaS with additional features of software development and implementation tools so that client could create and implement applications on a Cloud. Last but not the least is SaaS provides with readymade software and applications in line with the needs of the client. Service providers manage the software, applications and the computing infrastructure and practices full control on the services. These services can be accessed through internet with the help of web browser.

[1] investopedia.com/terms/e/erp.asp

On Premise ERP system is the most common and traditional ERP solution offered by the service providers. In this type of ERP, hardware and software implementation is carried out at the client's location according to its needs. Therefore, after implementation of the package, client exercise full control on its data and application. Manufacturing companies, banks, government institutes, insurance companies, health care centers all use this kind of ERP software for operations and management. SAP and Oracle are the most widely used ERP software in the world.

Web based ERP is the third type of ERP solution offered by service provide and it acts as an intermediate between traditional and cloud-based ERP software. It has a user interface of Cloud ERP i.e accessed through browser but does not need a large infrastructure like Cloud ERP.

1.5 Problem Definition and Objective of the Thesis:

Dissemination of different technologies in the manufacturing industry over the past few decades has led to multifold increase in the digital data. The biggest challenge at present for industrialists is to synchronize and integrate this humongous amount of data with each other. It would not be wrong to say that this big data is a source of knowledge cascade for the whole organization. This knowledge that takes ages to build up and accumulate is of empirical importance for the whole organization. This knowledge which is mostly in the form of data is unstructured and requires preprocessing and analysis techniques to be used in different information systems. Evidence of the need to structure and represent data in a more comprehensive way can be found by Marsh [6] who states "less than 50 percent of the companies claim to be very confident in the quality of their data".

Acquiring data is one challenge but transforming this data into performance analysis tool is another challenge. Using data at factory level to evaluate the performance of the companies at different vertical is of empirical importance. Defining performance metrics and key performance indicators for custom order firm is very challenging. There are several functions and departments in an organization that need to interact and work along with each other to transform an idea into reality. In fact, this co-working environment and knowledge dissemination is the basis for the existence of Product Life Cycle Management With growing demand for mass customization from customers, traditional way of designing and manufacturing the product has become obsolete. Most companies are still relying on manual techniques for information and data communication and end up in accumulating tacit knowledge. In this thesis, a knowledge-based system is analyzed which resolves the problem of tacit knowledge accumulation and eventually provide us with an opportunity to define and evaluate the key performance indicators for the company under case study.

Consumers are demanding high-quality personalized products. To support personalization of high-quality products, companies try to establish Information Technology (IT) systems, for instance, PLM and MES [7]. While PLM is used for product design, simulation, and testing, MES is used for production control and monitoring. Usually, there is another actor between them i.e., ERP. Due to lack of integration between MES and PLM data, a lot of time and cost is wasted even for small changes in design. Therefore, with the focus on medium enterprises we try to analyze the following research questions:

- *RQ: What are the elements and key performance indicators required to evaluate the performance of custom manufacturing companies by utilizing the knowledge based system?*

1.6 Outline of the Thesis:

The thesis consists of five chapters. The first chapter "Introduction" includes a brief outlook of manufacturing history, manufacturing knowledge, industrial systems and highlights the problem of data transformation into useful performance metrics. Second chapter is dedicated to existing literature review related to the topic of discussion and theoretical background with an emphasis on Manufacturing Operations Management and associated literature related to Key Performance Indicators. In the third chapter, Knowledge Based System and its associated tables are explained in detail which are used to define and calculate Key Performance indicators in the fourth chapter. Fourth chapter includes the implementation part of the approach used for the defining and evaluating the Key Performance indicators for the knowledge-based system explained in the third chapter. Last chapter of the thesis discusses the results of the approach and propose recommendations to improve the existing model. The outline of the thesis is shown in figure 2 on next page.

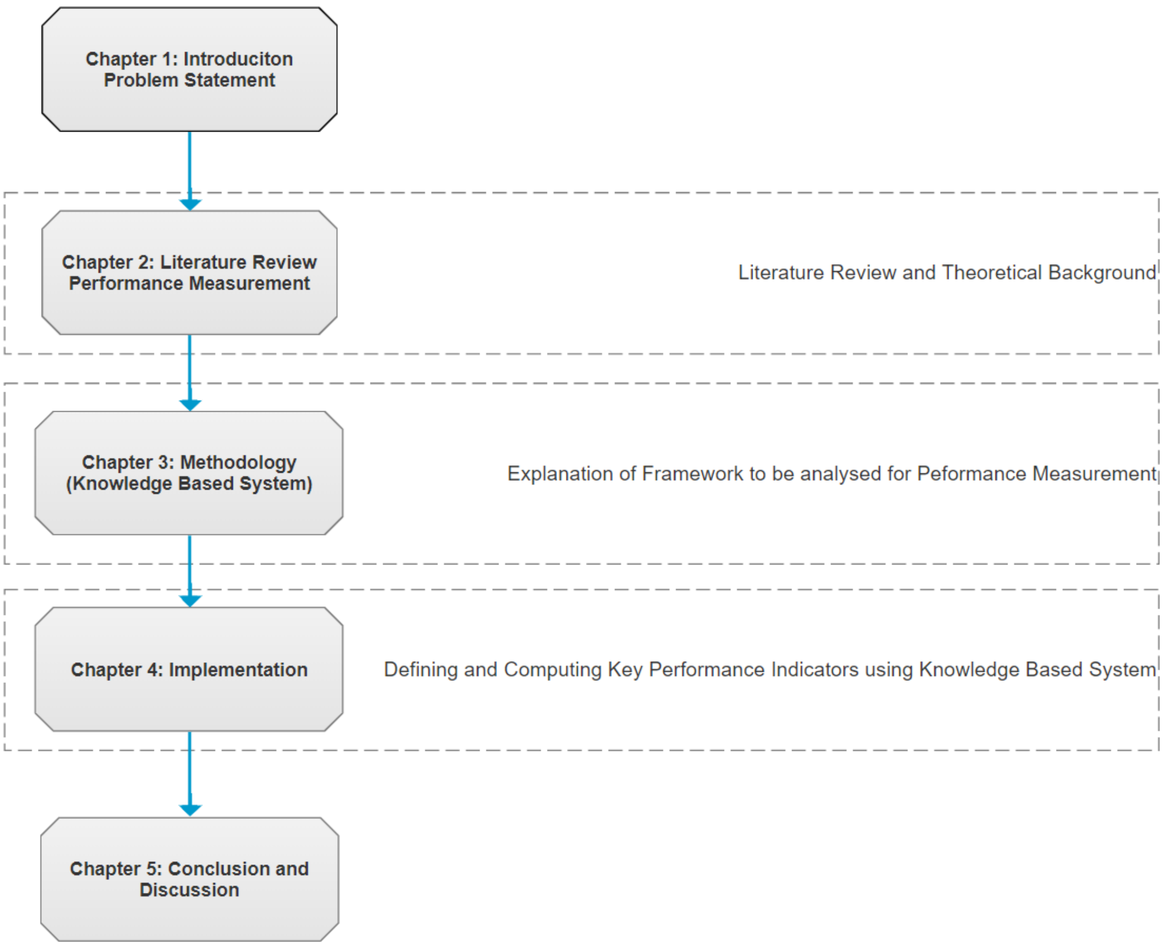

Figure 2: Outline of the Thesis

2. LITERATURE REVIEW AND THEORETICAL BACKGROUND

In this chapter, literature review is carried out considering various information systems platform such as PLM, ERP and MES. Moreover, theoretical background of Key Performance Indicators is discussed. Suggested research papers are read, highlighting the fundamental use of the platforms in the manufacturing industries. It is very interesting to note that, most of the research papers explain about the benefits and analysis of individual platforms. Very few research papers are based on the integration of MES and PLM platforms. This argument is asserted by the Venn Diagram shown in figure 3 along with the trend line spanning two decades provided by Scopus research. Here free numbers show the research carried out on the title alone. Whereas the numbers within the bracket refer to research carried out on title, abstract, and keywords. A great deal of research is still available talking about the integration of various platforms.

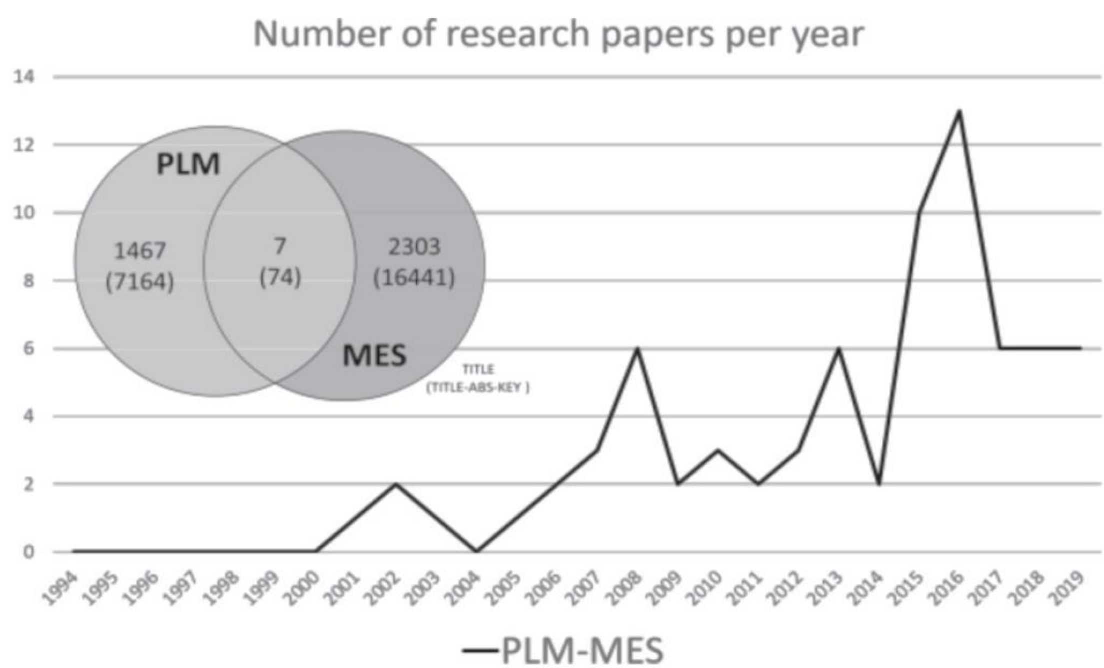

Figure 3: Number of Research Papers per Year

With the advancement in technology, every industry is shifting towards digitalization. Especially the manufacturing industry, which now, is moving towards industry 4.0 paradigm, requires a lot of digitalization in its different functions. Digitalization in a manufacturing industry is carried out by integration of multiple functions like PLM, MES and ERP system. Several research papers have been written considering advantages of this integration. Recently open-source framework was developed for the storage and reuse of industrial knowledge through the integration of PLM, MES and MES[1].

Before stating the methodology and implementation part of this thesis, a foundation must be built to prepare the reader to understand the terminologies and concepts associated with manufacturing know-how, interoperability of manufacturing systems, digital manufacturing, manufacturing operations management, integrated manufacturing, and integration of MES and PLM.

2.1 Manufacturing Know-How:

Any effort to define the term knowledge in an absolute way can be considered vain, a task that the ancient Greeks began and that researchers in modern society are still debating [8]. Knowledge is a comprehensive term that can be classified and categorized into various technological and scientific arrays. What is important is the correct storage and utilization of knowledge for value creation across the whole organization. Management literature broadly classifies knowledge into two categories: Explicit knowledge and Tacit Knowledge. Explicit Knowledge can be considered like knowledge gathered through facts and information. Whereas, our point of interest, tacit knowledge is context dependent and obtained through personal experience and is also referred as know-how [9]. A good example of tacit knowledge is skiing, it is difficult to explain how to do it, one has to experience it. Since unconscious abilities, skill and ingenuity are hard to codify[10] , there is a need for development of knowledge based system which not only accumulates the information but also helps manufacturing firms to reduce time and cost associated with the design and production of the product.

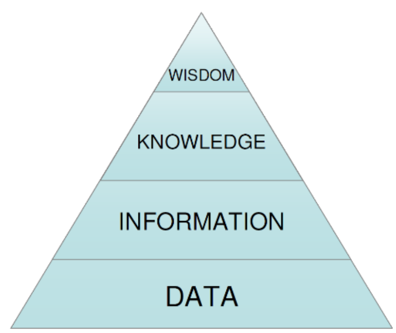

Figure 4: Knowledge Pyramid

Chep and Anselmetti (1993) suggested a conceptual model for the representation and use of manufacturing knowledge. The model was aimed at automating the process planning steps begore the start of production activities. It was deduced during research that manufacturing know-how is volatile and subjective and usually requires analysis to be represented in a legible form. Therefore this knowledge of know-how was classified as implicit and context dependent[11].A notable mention in the knowledge management and information science domains is DIKW (Data, Information, Knowledge, Wisdom) pyramid researched by various authors distinguishing the abstract concepts of raw data, information, knowledge and wisdom[12]. As shown in figure 4, the lowest level of the hierarchy contains raw data that needs further processing and analysis to extract the useful information from it. After the perspective regarding information is clear to the enterprise, this information is communicated across concerned department related to product development and manufacturing. The next level in this knowledge pyramid is of vital importance since our knowledge-based system is based on the transformation of tacit knowledge into useful and codified knowledge. This level of the pyramid is our topic of interest and we have developed a model to integrate knowledge sharing between MES and PLM. The last level of the pyramid is still vague as more research is needed in this regard. But if an enterprise has an integrated knowledge-based system then it can leverage this opportunity to reach to the last level where it is able to make the company functions as efficient as possible.

2.2 Manufacturing System Interoperability and Integration:

Interoperability can be defined as that inherent characteristic of a standard entity (organization, system, process, model …) allowing its interaction with other entities - to a different extent of simplicity - to co-working purposes, within a definite interval of time [13]. The standard for advanced manufacturing technologies **CEN/TC 310** has identified three levels of integration: 1) Physical Integration (interconnection of machines, PLCs, electronic devices via computer network) 2) Application Integration (interoperability of enterprise wide software applications and database systems in heterogenous domains) 3) Business Integration (organization of functions that manage, control and monitor business processes). It depends on the enterprise’s objectives and goals, which level of integration they want to achieve in their business functions. Essentially, integration is more complicated than interoperability since it involves some degree of functional dependence. This argument is asserted by the fact that an interoperable system can function independently, but an integrated system loses its functionality in the event of interruption of services. This takes us to propose a generic statement that integrated systems must, necessarily, be interoperable but interoperable systems might not be integrated. In a similar fashion, a relationship can be defined between compatibility and interoperability can be built. Compatibility means that systems do not interfere with each other's functioning, but it does not mean that they are able to exchange services. Whereas an interoperable system ensures the exchange of services with other systems without any interruption. Therefore, we can conclude that interoperable system is necessarily be compatible but the contrary is not necessarily true[14].

Product driven manufacturing has emerged as a new paradigm in manufacturing industry where all the phases of the product development are synthesized by keeping product as the focal point. Since many departments are engaged in product development; from design to manufacture, from sales to end user support, different information systems interact with one another to facilitate one another. Integration of theses information systems platforms and manufacturing systems is one of the success of enterprise modelling. In fact, integration in manufacturing domain is perceived as the first paradigm towards organization of humans and machines as a whole system, including field, management, and corporate levels. As a result we get an interoperable and integrated enterprise[15] . Moreover, recent advances in information and communication technology in manufacturing industry have shifted the paradigm from data driven environments to more knowledge and information sharing environments. But this integration of information environments and systems comes with a cost.

For a smooth integration of business and manufacturing applications during the whole product life cycle, there is a need of utilizing enterprise engineering models and tools. Despite advancement in product oncology models for manufacturing interoperability, there is a lot of room for improvement. Henceforth, standards like ISO 10303 and IEC 62264 were proposed to resolve the issues related to interoperability problem by modelling definition of products information and validating the knowledge related to product technical data.

Enterprise-wide integration and interoperability is more important amid technological changes due to increased competition and rapid developments in innovative systems. This problem is of great concern to enterprises because if their systems are easily interoperable then technology dissemination becomes easier. The main objective of an organization is to achieve business through physical and application integration to enable exchange of information and communication.

The issue of enterprise interoperability is so important that international organizations and standards committees are constantly working to resolve issues and problems faced by companies in the domain of organizational integration and interoperability. For instance, European Commission has developed a road map related to enterprise interoperability under FP7 (Framework program 7) initiative. They have identified four major challenges that pave a way for long term strategic direction for enterprise interoperability research. They are: 1) Interoperability Service Utility (ISU), Leveraging Web Technologies for Enterprise Interoperability, Knowledge Oriented Collaboration, and a science base for enterprise interoperability. All these research domains are pointed towards different aspects that could enhance the performance of organization by bridging the gap between organization interoperability and success. Now we move on to the next discussion in which we will talk about the problems at discrete level related to enterprise interoperability i.e., Data Heterogeneity.

2.3 Problem of Data Heterogeneity:

Heterogeneous applications store, process and communicate information in different ways depending on the context they are developed and used. This heterogeneity of applications induces a sort of “Babel tower effect”, which causes traceability problems, leading systems to fail at collecting information from different and heterogeneous sources to effectively trace the product lifecycle [13].

Data heterogeneity arises when diverse data sets are flowing inside a unified system from different functions of the company. This leads to an exponential growth in the data volume and might cause problem. To tackle this problem, an organization needs to implement a robust data integration solution that could handle disparity and large volume without losing performance in the context of manufacturing.

To overcome this issue of data heterogeneity, a methodological approach was developed offering a mediation system resolving semantic and syntactic issues [16]. In global product lifecycle, the success of design, industrialization and production activities depends on the ability to make interactions among these modules as efficient as they can be. Over the last decade, the use of PLM concept associated to the development of PLM support activities have generated significant evolution in ERP systems.

The development of information system for controlling production led to the standardization by the ISA 95-IEC 62264 standard of MES functions and data structures exchanged between ERP and MES. Due to varied vendors of ERP and MES systems, this standard helps to standardize the integration. According to traditional architecture, product data needed for production management like planning and scheduling activities are saved in ERP system. Similarly, product data related to production activities are stored in MES. The interaction of above-mentioned information systems with innovative technologies like machine learning, internet of things and big data make the realization of industry 4.0 possible.

2.4 The Role of Industry 4.0 in Manufacturing:

Until now, the world has seen four industrial revolutions bringing new methodologies and changes to industrial manufacturing. First industrial revolution occurred in 18th century after the breakthrough in steam technology and its application in industrial domain. Following the first

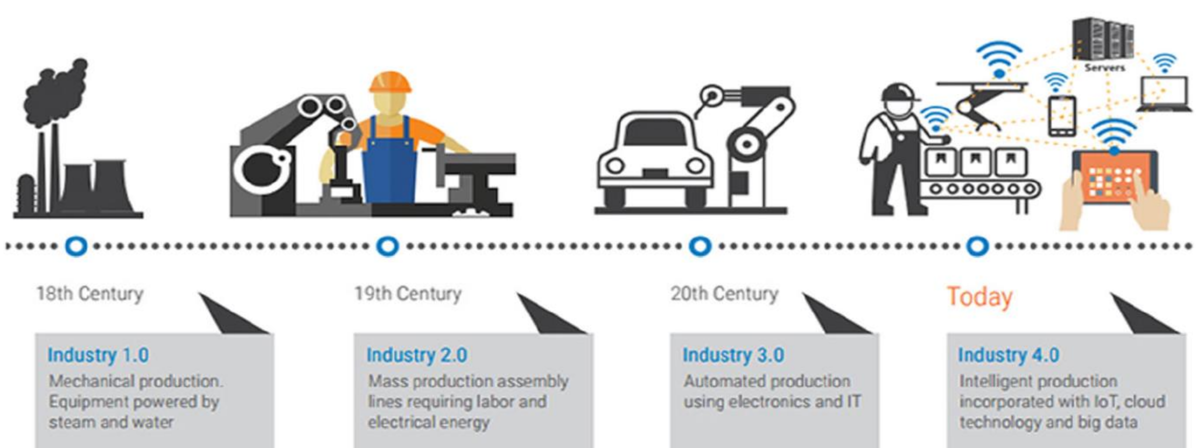

Figure 5: Depiction of four Industrial revolutions. BCMCOM (2017))

industrial revolution came the second industrial revolution, which introduced the use of different sources of energy like coal, gas, and light. It also enabled the mass production of goods with the help of assembly lines. Third industrial revolution is marked by automated production using electronic devices, computers, and programmable logic controllers. Industry 4.0 is the fourth industrial revolution that is happening right now with the most important driver: internet. The idea of connected device, intelligent production, internet of things, could technology and big data be some of the breakthroughs of this industrial revolution.

The term Industry 4.0 is often perceived as the application of the concept of Cyber Physical Systems (CPS) [17] to industrial production system. In USA, GE coined the word "Industrial internet" to describe the similar concepts related to interconnectivity and usage of data for its equipment[2]. While researchers focuses on understanding and defining the construct and trying to develop related systems, business models and respective methodologies, industry, on the other hand, focuses its attention on the change of industrial machine suits and intelligent products as well as potential customers on this progress [18]. In fact, the realization of industry 4.0 term happened in 2011 at Hanover Fair, Germany, where a group of representatives from different fields introduced this concept to enhance the competitiveness of German manufacturing industry.

Industry 4.0 as apparent by the explanation before tends to make an overall connected environment in the industrial space not bounded by regional, technical, and demographical space. With the increase in customer requirements and increased demand for speedy delivery of products, there is a need to remove all the value decreasing functions. By incorporating technologies and use of robots, value adding functions in the industry can be increased tremendously. The industry 4.0 regime supports the use of unmanned factories firmly connected globally through supply chains and sensor networks. For instance, if a product needs to be manufactured in a country other than its main manufacturing facility, technologies like 3D printing can be utilized.

[2] https://www.technologyreview.com/2012/11/28/114725/general-electric-pitches-an-industrial-internet/

Global trends like regional, economic, technological, and meta (about scarce resources, safety) are shaping the future of business and manufacturing. This important trigger in the business world requires efficiency and productivity in the manufacturing world which can be employed through use of connected systems, devices, internet of things, and big data. Therefore Industry 4.0 aims to make it possible to prepare and analyze data from the machines for this purpose. As a result, enterprise gets flexible, faster, and more efficient processes to manufacture higher quality products. Moreover, as mentioned in the previous discussion, the target areas for industry 4.0 are factory, business and products. In fact, based on the main drivers of the value chain, Qin et al. (2016) proposed a framework for Industry 4.0 system. They analyzed the components of industry 4.0 in four layers: Factory, business, products, and customers [19]. Having discussed about Industry 4.0 and its components, we can move on to the trends and challenges faced by digital manufacturing.

2.5 Product lifecycle Management and Digital Manufacturing:

PLM is considered to play an imperative role in integrating the information related to product, processes, and resource development during different phases of product life. A lot of research has already been done in the domain of PLM. But with the advent of novel and game changing technologies like Cloud Computing, Internet of things, and big data, there is a need for restructuring of legacy base PLM systems used by the company. By digitalizing the overall product life cycle management comes many obstacles and challenges. It is not only the amount of data that is and will be available as a result of digital paradigm shift but also the number and diversity of advanced digital manufacturing technologies that make the management of integration of data a very complex task[20].

Due to ever evolving trends in the current markets, manufacturers are facing stringent challenges such as shorter product lifecycles, highly customized products, lower bottom line, increased supplier network dispersed in different geographical locations, increased pressure to reduce energy and material requirements. In this context, enterprises are striving to improve their operational and production efficiency, reduce manufacturing and logistical costs, shorten the product life cycles and maximize the value of products for customers and stakeholders[21].

Consequently, firms have directed their vision towards mega digital trends like big data, internet of things, and cloud computing to optimize and speedup their production.

Cloud computing coupled with Product lifecycle management tools has the potential to support manufactures during different phases of PLM in terms of products, process, and resource management. Essentially PLM is a broad concept that has transformed from a generic engineering oriented application to enterprise level application over the passage of time[22].

PLM in principle is an evolution of Production Data Management (PDM). PDM constitutes five major functions [23]:

i. Information storage system to store product data in an organized manner
ii. Information management of modules employed for data access, security, system administration, recovery, and concurrent use of data
iii. Workflow management modules for defining and regulating workflows
iv. User interface to entertain user requests
v. Interface for integration with other applications such as Computer Aided Design (CAD) and ERP (Enterprise Resource Planning)

The demand for mass customization and one-of-a-kind product also requires information about the use of product. Smart digital devices has enabled to create an information loop closure, permitting the use of product usage data, which can eventually help in improving the product and process design[24]. Moreover, companies are constantly searching for alternatives to increase product quality, shorter time to market and competitiveness. This concept has made the realization of product-as-a-service possible. In Product-as-a-service offering, using digital platforms, customers are offered products, services and monitoring capabilities as a part of subscription package. This type of offering enables real time monitoring of product in use using networked services, where manufacturers look beyond the manufacturing service [20]. As a result, PLM systems becomes an entity of digital manufacturing environment. This conceptualization, associated with design, development, manufacturing, and service of high value products such as airplanes, trucks, and heavy mechanical machinery, is extending PLM capabilities into areas previously managed by ERP and SCM[3].

2.6 Integration among Industrial Systems (PLM, MES and ERP):

So far, we discussed about prevailing technologies being applied in the manufacturing industry to cope up with ever growing customer demand and challenges. Now, we put some light towards the integration of most important entities of manufacturing eco system. Information systems like Product Lifecycle Management (PLM), Enterprise Resource Planning (ERP) and Manufacturing Execution Systems (MES) are among the mostly deployed systems in modern manufacturing companies (Ben Khedher et al., 2011). According to the study "Integrating the PLM ecosystem conducted by Aberdeen Group in April 2018 based on a survey of 260 companies, the manufacturing processes of the product is stored 15 % in PLM, 36% in ERP, 23 % in MES, and finally even more surprising 26% in another system or not. Such a distribution of data storage reveals the stringent absence of data management and monitoring of processes that generate such data. Therefore, it poses a challenge of continuous product related data flow from design to production.

2.6.1 Integration between PLM and ERP:

While implementing ERP and PLM in an organization, there are several factors related to production, organization structure, culture, and technological aspects to be considered[25] . When considering the integration between ERP and PLM, there are various approaches and methods which depend on the level of complexity of integration, and cost and time associated with the development of framework for integration. This integration offers the customers to have hands on access to a complete package of pre-built application and technology integration, as well as Graphical User Interface (GUI) business logic development and administration environment, pre-building the necessary business logic to support the publishing of many different types of product information to ERP [26].

[3] https://www.engineering.com/story/plm-at-scania-heavy-trucks-smart-vehicles-porsche-design-and-a-looming-vendor-battle

First, data to be exchanged between ERP and PLM must be identified and workflow must be formulated according to the organizational needs. Data related to manufacturing system should be stored and managed by PLM. Another important aspect to be noticed is the interaction frequency between PLM and ERP, which again depends on the level of complexity of product to be manufactured. Integration framework developed in this research facilitate the sharing of data between design and production teams. In this way engineering team can also search business and financial aspects of the project by accessing the ERP portal. Synchronizing the above platforms will also allow the dissemination of innovation, collaboration, and productivity between different departments. Some enhancements are also proposed in the current environment to fully utilize the benefits of integration. The enhancements are common business objects, simple object access protocol, integration of design and manufacturing tools.

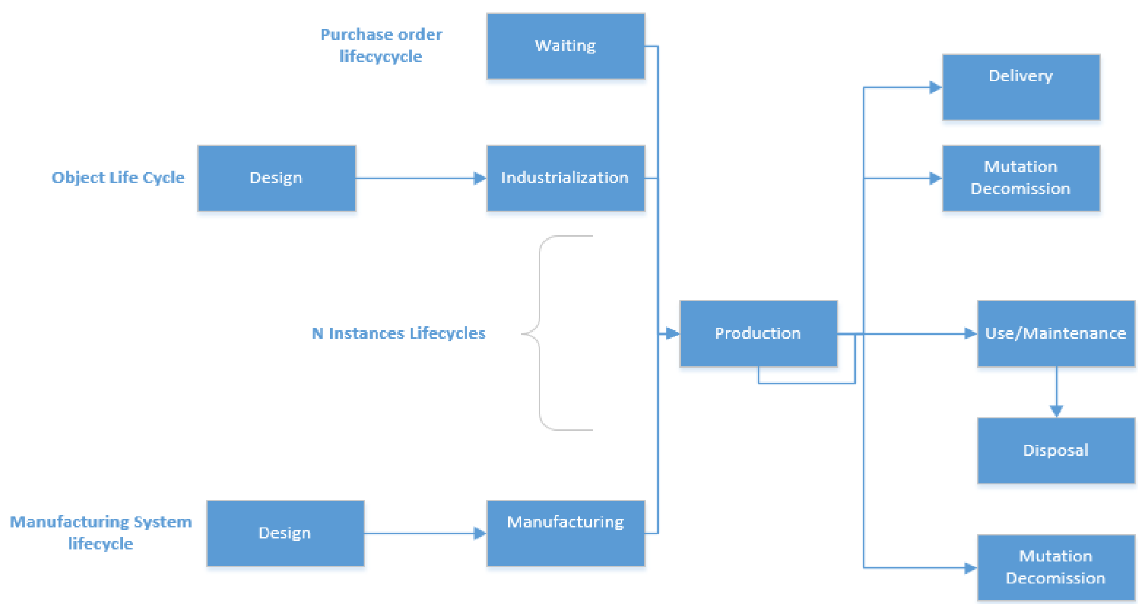

Figure 6: Lifecycles in the context of PLM [16]

2.6.2 Integration between MES and PLM:

The integration between PLM and MES is variable depending on the solutions required by the company and depends on various factors such as product type that can be customized and manufactured to customers request or manufactured from stock [16]. MES-PLM cooperation is essential for successful development, manufacturing and launch of product in this dynamic world. Where PLM system manages product and process related information, MES keeps a close eye on the real time data generated during production activities. Therefore, the information generated during manufacturing can be converted into knowledge can be utilized in terms of redesign or revision of product or production processes. A successful integration between PLM and MES can play a key role in process performance and product quality improvement.

Khedher et. al (2011) proposed a methodological approach to integrate product data during its design, development, testing, and manufacturing. In other words, they tried to make a model for PLM and MES integration. In the model they first analyzed different lifecycles without considering the product and its impact on the frequency and timing of data exchanges between information systems. Secondly the model takes into the account the data exchanges between systems that needs to be automated. Lifecycles discussed are product instance lifecycle, object lifecycle, manufacturing system lifecycle, and purchase order lifecycle shown in figure 6. By analyzing different interactions among lifecycles, it is found that production activity is the meeting point of them. After identification of activities of each life cycle, a classification of activities is carried out according to two criteria: activity type and activity output. Activity output means what kind of output each activity would generate. For instance, the output of designing activities is a virtual model (CAD mode), whereas the output of the manufacturing activity is a physical object criterion is activity type: certain or uncertain. Certain activities are those activities that are known beforehand start of the operation. Whereas uncertain activities are not a priori known. From these two criteria, it is possible to define four categories of activities: Data-Certain, Data-Uncertain, Physical Effect-Certain and Physical Effect-Uncertain. Comparison of current coverage and proposed coverage reveals that activities not covered by these solutions are handled manually or using tools developed specifically which can cause limitation of flexibility of information system. In most current solutions on the market, a part of the industrialization stage, the whole of marketing stage and disposal stage are no longer managed by PLM systems. To address this gap between current and required coverage, they proposed a solution that allocates the data-certain activities to ERP, data-uncertain activities to PLM, physical effect-certain activities to MES and physical effect-uncertain activities to other tools. In this way, data can be utilized in an efficient manner across the three systems.

2.6.3 Integration between ERP and MES

The improvement in the production processes and tracking and controlling of real time data is a need of every manufacturing industry. For this purpose, most enterprises widely rely on MES for end-to-end control and monitoring. In many SMEs, usually these systems are not integrated well for process monitoring or either one or none are present. This information generated by MES can be converted into manufacturing knowledge that can eventually help in redesign and revision of product or manufacturing operations.

Moreover, such information system allows the possibility of quality, synchronized and real time control over all the stages of product life cycle management. The application of information and communication systems in production has threefold effects: it can significantly affect time usage (work efficiency), improved quality of the product, and less price of the product. The importance of MES systems in industrial production enterprises and their usage along with the usage of ERP is empirical. Information systems used for production management have a lot of interested parties like software developers, management, and end users. The interaction of such parties is of vital importance to develop an efficient and optimize software solution.

Beric et. al (2020) proposed an MES system for a company which has an existing ERP system[27]. Software solution integration was developed for the company with different manufacturing sites at different locations whose ERP system was in place with all the functions of ERP system connected. But the monitoring of the operations in all these sites was not closely monitored and tracked. The company under study did not have an MES system, therefore there was a need to develop a software solution to support the management of industrial enterprise. To implement the software solution lifecycle methodology, prototype approach, object-oriented approach and Larman's method was used.

MES system are mostly used for generating and tracking documentation throughout the production cycle. It provides information in real time which helps to take decision regarding the changes related to production parameters and inputs. MES systems can be visualized as an interlayer between ERP and SCADA system. There is no denying the fact that the implementation of software systems like ERP and MES require the alignment of business strategy of an organization and use of a lot of resources and time.

2.7 Manufacturing Operations Management:

Operations management is defined as "the activity of managing the resources, which produce and deliver products and services"[28]. Manufacturing operations management (MOM) is a holistic approach that gives full visibility of production operations to improve overall manufacturing performance of the enterprise. In an enterprise, daily production activities, resource and personnel management, scheduling, reliability assurance, record management and optimization of production processes come under the umbrella of MOM. In fact, MOM term is also used in IEC 62264 standard to hilght a portion of functional hierarchy model shown in the figure 7.

MOM consists of four categories of operations: production operations management, maintenance operations management, quality operations management, and the inventory operations management.

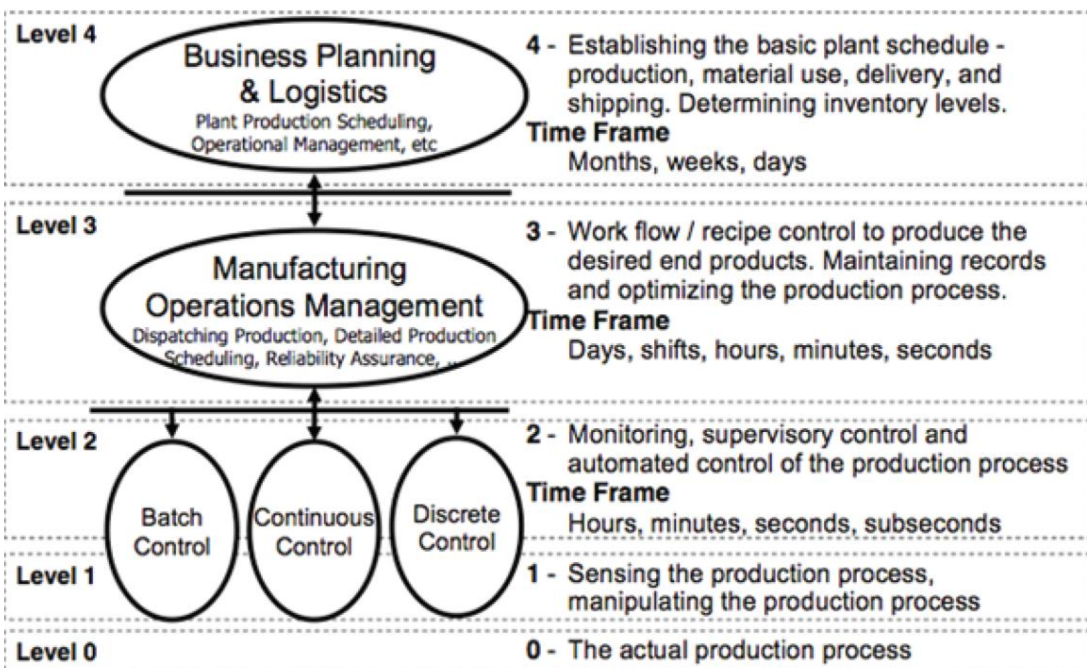

Figure 7: Functional Hierarchy Model adapted from IEC 622643 [38]

These categories serve as the foundation of MOM. In line with our research question number 3, we are interested in selecting the Key Performance Indicators residing at level 3 (MOM) of the functional hierarchy model. These KPIs are calculated with the help of level 1 and level 2 of functional hierarchy model. Let's now direct our focus towards the literature related to KPIs.

2.7.1 Concept of KPIs:

KPIs are defined as the quantitative and strategic measures that reflect the enterprises critical success factors[29]. KPIs are an efficient and effective way of improving the performance of the company in all its operation areas such as manufacturing, engineering, marketing, and sales. As our research is in the domain of manufacturing so we will focus our attention to the definition of KPIs that are prevalent in manufacturing industry. The most consistent cited standard in this regard is ISO 22440, which is the international standard for automation system and integration for manufacturing operation management. ISO 22400 emphasizes on those performance measures which are meaningful for the realization of operational performance improvement. These performance measures can be obtained by combining various operation variables which ultimately gives us key performance indicator. The goal of this comprehensive performance monitoring is the fulfillment of enterprise objectives. Moreover, these performance metrics can be used as benchmark for comparison of performance over extended period within an enterprise or comparison of performance between enterprises within the same industry.

IEC 62264 is an international standard for enterprise-control system integration. This standard is based on ANSI/ISA 95 model. IEC 62264 defines a functional hierarchy of business's operations having five different levels along with time horizon and systems administered. This hierarchical model vertically cuts the systems of manufacturing operations into different levels that can be connected to certain types of information, systems, and timeframes, which have been defined in a standard model by International Society of Automation [30] .

As shown in figure 8, level 0 refers to actual production process at the very basic discrete level consisting of control signals and sensors connected with the equipment and machines. Level 1 corresponds to a higher level of data collection and manipulation using Distributed control systems and programmable logic controllers. Similarly, at level 2, supervision, and monitoring of the manufacturing operations at the lower levels take place with the help of human machine interface and SCADA. At the intermediate level comes the MOM (Manufacturing operations management) responsible for the supervisory level workflow management of the desired products, maintenance of records, and optimization of the production process. At this level, as expected, the time horizon of data collection extends over hours given the abundance of data to take care of. Last but not the least, we see level 4 residing at the top of functional hierarchy.

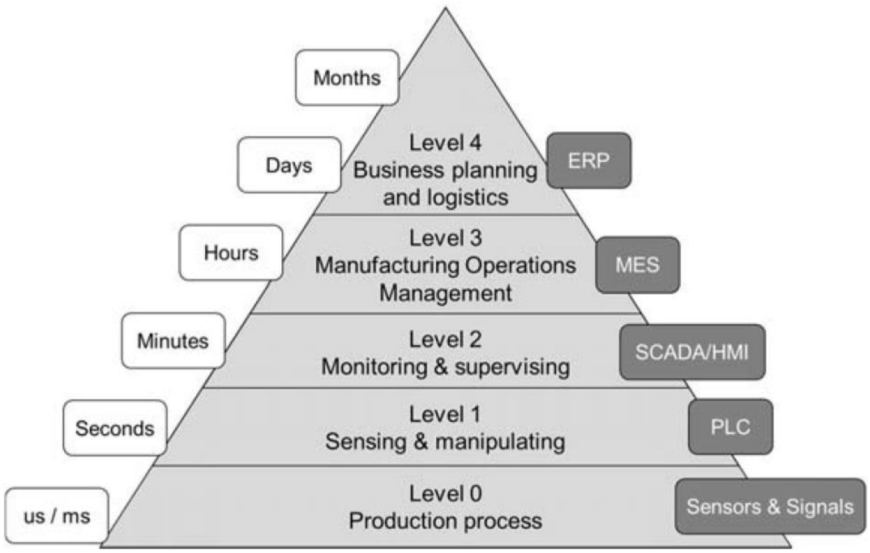

Figure 8: Functional Hierarchy ISA 95 Model

The ISO 22400-1 presents an overview, concepts, and terminology for key performance indicators. ISO 22400 defines a list of 38 KPIs which are meant to be industrial neutral and can bee have applied at any level of the organization. Generally, an enterprise is described by three hierarchical models:

1. Physical assets
2. Functional
3. Equipment

For our context, we will target functional and equipment hierarchical modes as they are consistent with the manufacturing operation management domain.

2.7.2 Criteria for Selecting KPIs:

While selecting the KPIs for an enterprise, it should have certain criteria. A good KPI is defined as the performance metric which is useful and applicable in the target context achieving main objectives of the enterprise. Some of the criteria providing the significance of KPI in ISO 2240 are following:

a) **Aligned:** KPI must be aligned in a way that it affects in a positive way the higher KPI achieving the performance improvement at an enterprise level.
b) **Standardized:** A standard for the KPI being implemented should exist and the standard must be correct, complete, and ambiguous; scope of the standard can be plant-wide, corporate-wide, or industry-wide.
c) **Balanced:** Balancing corresponds to selecting KPIs that complement one another[4]. It means that while selecting KPIs, we must keep in mind multiple perspectives. Balancing approach refers to quantity and quality; subjectivity and objectivity; and efficiency.
d) **Valid:** The KPI must be valid syntactically and semantically and show a compliance between the operational definition of the KPI and the standard definition.
e) **Quantifiable:** The value of the KPI can be numerically expressed and there is no penalty for uncertainty if the uncertainty can also be quantified.
f) **Accurate:** The measured value of the KPI should be close to the true value. The deviation from the true value can be possible due to poor data collection, poor accessibility to the measurement location, or faulty instrumentation and tools.
g) **Timely:** The KPI must be able to be computed in real time, where real time depends on the operational context.
h) **Predictive:** The KPI must be able to predict the non-steady state operations**.**
i) **Actionable:** This criterion is related to the actionability of the team responsible for the KPI in terms of its knowledge, ability, and authority. The team must be able to improve the value of KPI within their own process.
j) **Trackable:** The temporal trend of the KPI must be able to help in diagnosing the problem. Ultimately the steps to take to solve the problem must be known, documented and accessible.
k) **Relevant:** The KPI must be relevant in a way that it enables performance improvement in the target context, predicts the future events, demonstrates real time performance, and shows the past performance for feedback and control.

[4] https://www.performancemagazine.org/kpi-balancing-important-businesses/

l) **Correct:** The KPI is correct to the extent that calculation required to calculate the KPI must be equal to the one obtained by standard definition (if one exists).

m) **Complete:** The KPI is complete in a way that the definition of the KPI and calculation required to compute the value of KPI must be complete and in line with the standard.

n) **Unambiguous:** KPI is unambiguous in way that the definition of KPI semantically and syntactically lacks ambiguity and uncertainty.

o) **Automated:** KPI's data collection, computation, implementation, and reporting should be automated.

p) **Buy in:** The team responsible for the target operation and even upper and lower KPIs must support the utility of KPI and help in achieving the target value for the KPI.

q) **Documented:** The registered instructions for the implementation of the KPI must be up-to-date, complete, correct and have instructions related to how to compute KPI, and what measurements are necessary for its computation and what actions to take for different KPI values.

r) **Comparable:** The KPI is comparable to the extent that means are defined to indicate supporting measurements over a period and there should be a presence of normalizing factor to transform the KPI in absolute terms.

s) **Understandable:** The most important criteria are understandable. KPI should be comprehend by the team members, management, and customers with respect to corporate goals.

t) **Inexpensive:** From financial point of view, the cost of measuring, computing, and reporting the KPI is low.

2.7.3 Characterization of KPIs:

To completely describe a KPI, it is characterized by its content and context. Content of KPI includes all the details about its name, id, scope where it is applied, formula and unit of measure. Similarly, context as the term suggests contains information about the timing, audience, production methodology, effect model diagram and notes. The structure of KPI description is given in table 1 on the next page.

KPI description	
Content	
Name	Name of the KPI
ID	A user defined unique identification of the KPI in the user environment
Description	A brief description of the KPI
Scope	Identification of the element that the KPI is relevant for, which can be a work unit, work centre order, product or personnel
Formula	The mathematical formula of the KPI specified in terms of elements
Unit of measure	The basic unit or dimension in which the KPI is expressed
Range	Specifies the upper and lower logical limits of the KPI
Trend	Is the information about the improvement direction, higher is better or lower is better
Context	
Timing	A KPI can be calculated either in • real-time - after each new data acquisition event • on demand - after a specific data selection request • periodically - done at a certain interval, e.g. once per day
Audience	Audience is the user group typically using this KPI. The user groups used in this part of ISO 22 • Operators – personnel responsible for the direct operation of the equipment • Supervisors – personnel responsible for directing the activities of the operators • Management – personnel responsible for the overall execution of production
Production methodology	Specifies the production methodology that the KPI is generally applicable for • Discrete • Batch • Continuous
Effect model diagram	The effect model diagram is a graphical representation of the dependencies of the KPI element used to drill down and understand the source of the element values. NOTE This is a quick analysis which supports rapid efficiency improvement by corrective acti reduces errors
Notes	Can contain additional information related to the KPI. Typical examples are • Constraints • Usage • Other information

Table 1: KPI Structure Description

2.7.4 Classification of KPIs:

To better visualize the direction of improvement in one of the operational areas a company wants to pursue, it is imperative to have a relevant KPI in that area. Although ISO 22400 segregated the elements that are used for KPI evaluation, it did not provide any information regarding the broad classification of 38 KPIs. To bridge this gap, Yuriy et al. in 2019 proposed a framework to divide 38 KPIs defined by ISO 22400 into five types based on different processes in the manufacturing systems [3]. The division is shown in table 2 and table 3. Moreover, major types of KPIs discussed in research paper are as follows:

2.7.4.1 Production Operations Management:

These KPIs are associated with the control and monitoring of production lines ensuring timely flow of production orders. They also assist in scheduling of machines and work orders. The personnel involved in dealing with such kind of KPIs are product managers and line operators working on the line. Examples include availability, allocation efficiency, utilization efficiency and technical efficiency.

2.7.4.2 Maintenance Operations Management:

KPIs required for the maintenance of manufacturing resources such as machines, robots, conveyors, and tools etc. fall in this category. These KPIs are used to analyze the activities involved during corrective and predictive maintenance. KPIs in this category are mean time to failure, setup rate, mean time to restoration and corrective maintenance ratio.

2.7.4.3 Quality Operations Management:

These KPIs are responsible for the performance of production line in quality perspective. Essentially, top level management is particularly interested in these KPIs as they indirectly define the corporate image of the company. Examples include quality ratio, rework ratio, and actual to planned ratio.

2.7.4.4 Inventory Operations:

KPIs include in this category are related to the logistical and inventory management activities such as transportation of raw materials from warehouse to work centers, release of finished goods and warehouse storage. For example, inventory turn and finished goods ratio.

2.7.4.5 Energy Management:

All the activities related to energy consumption and management across the plant site are controlled by these KPIs. These KPIs have gained importance specially in the field of sustainable

Key Performance Indicators	Type of KPIs		
	Production	***Inventory***	***Energy management***
Worker efficiency	V		
Allocation ratio	V		
Throughput rate	V		
Allocation efficiency	V		
Utilization efficiency	V		
Overall equipment effectiveness index	V		
Net equipment effectiveness index	V		
Availability	V		
Effectiveness	V		
Inventory turns		V	
Setup ratio	V		
Technical efficiency	V		
Production process ratio	V		
Machine capability index	V		
Critical machine capability index	V		
Process capability index	V		
Critical process capability index	V		
Comprehensive energy consumption	V		
Finished goods ratio	V		
Integrated goods ratio	V		
Production loss ratio	V		
Storage and transportation loss ratio		V	
Other loss ratio		V	
Equipment load ratio	V		
Direct energy consumption effectiveness			V

Table 2: Types of KPI(I)

manufacturing since the goal is to reduce the energy consumption and carbon footprint. For example, we have direct energy consumption effectiveness, direct energy efficiency and direct net energy con effectiveness.

Key performance indicators	Types of KPIs	
	Quality	*Maintenance*
Quality ratio	V	
Actual to planned scrap ratio	V	
First pass yield	V	
Scrap ratio	V	
Rework ratio	V	
Fall off ratio	V	
Mean operating time between failures		V
Mean time to failure		V
Mean time to repair		V
Corrective maintenance ratio		V

Table 3: Types of KPI(II)

Table 2 and Table 3 divides different KPIs based on their elements used for their calculation. For instance, in table 4, KPIs having elements related to the functions of quality and maintenance are segregated. Similarly, table 3 divides the KPIs based on the elements corresponding to production, inventory, and energy management

2.7.5 Types of KPIs by unit of measure:

Based on the application, the value of the KPI can be one of the following types:

- **Ratio**: a functional relation between two elements of the same unit-of-measure
- **Utilization:** a ratio with time as the unit of measure

- **Efficiency:** ratio of effort performed to the effort available
- **Effectiveness**: ratio of planned or expected value to an observed value
- **Rate**: it is a relationship between two entities with different unit of measures and time in the dominator
- **Capability Index**: measure of the fit of the characteristic of the source to the task Delegated

2.7.6 Tools for Visualization of KPIs:

Measuring process and production elements with the help of sensors at the lowest level of equipment hierarchy allows us to compute Key Performance Indicators. The work is not finished here, we still must display the results of KPIs for better monitoring and control of the process. This task is done by Information and Communications Technology which provides us with the tools and techniques for monitoring and supervision of performance of industrial systems. Ferrer et al. (2018) proposed an approach for the implementation and visualization of a set of KPIs defined in the ISO 22400 standard-Automation systems and Integration, for manufacturing operations management [31].

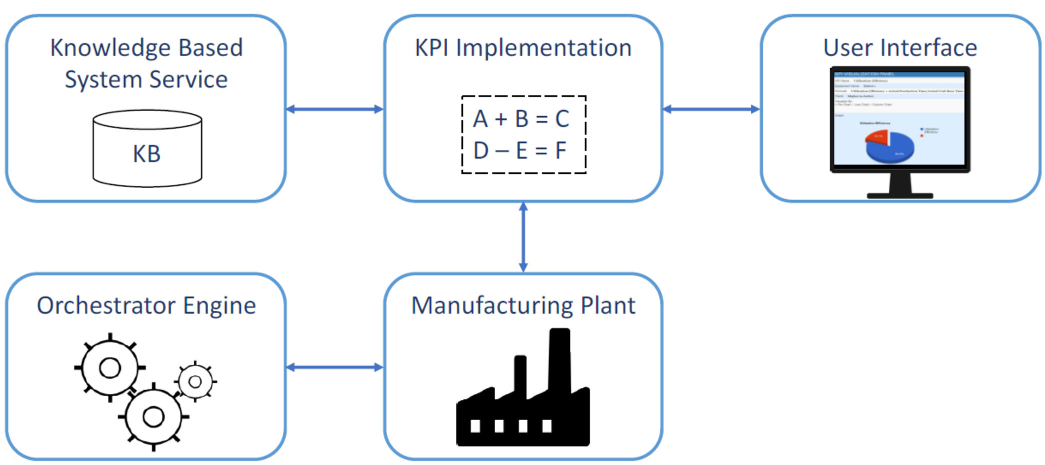

Figure 9: Five main components of the Approach

The approach consists of five components shown in figure 9 that enable communication between each other to provide better visualization to the user. The five components are: The Knowledge based System Service, the Manufacturing Plant, the Orchestration Engine, the KPI implementation and the User Interface. User interface is the entity responsible for the visualization of selected KPIs.

The visualization provide by the approach is updated in system run time by the consumption of manufacturing plant event notifications and retrieval and update of knowledge form and to an ontology, respectively [31].

2.7.7 Interdependency of KPIs and KPI Elements:

A production system is a very complex system including a lot of actors and entities controlling it or directly influenced by it. Various dependencies and covariances exist in such a system since the components of the systems relate to each other. Therefore, the metrics used to analyze or monitor such components are directly or indirectly connected to other parts of the system. That is why special attention should be given while selecting the metrics for performance analysis. Neglecting these measures can lead to conflicts, since these measures can work in an opposite way.

For instance, Overall Equipment Effectiveness (OEE) is a KPI which combines information from different dimensions like quality, availability, and effectiveness. This KPI has a multifold effect on the performance of various functions within an industry. Therefore, the designer of PMS should be vigilant while defining metrics for this KPI. Another example could be the KPI ‘Quality Ratio’. Quality manager will focus on high quality ratio by increasing the repair and maintenance time of the plant [32]. As a result, there will be less defects in production or low-down time. But the production management department would like to increase the actual production of the plant increasing the effectiveness by decreasing the total repair time. Hence there is a conflict between these two measures of production.

2.7.8 Improvements in ISO 22400 KPIs formulation:

Substantial research has been done regarding the extension and improvements of KPIs by a lot of authors. Although ISO 22400 is a very comprehensive standard regarding the overview, definition, and description of Key Performance Indicators but there are a lot of areas where an improvement is possible. Varisco et al., in 2018, provided a framework for the practical applicability of Key Performance indicators for MOM defined by ISO 22400[33]. According to the authors of the research paper, the general contents of the standard are beneficial for the wide application of the KPIs in an industry neutral environment, but they also cause an impediment. They say high abstraction level of general descriptions of KPIs make it difficult to judge what they relate to. They further emphasize that the elements and KPI context information are often ambiguous and imprecise and provide information may be fragmented. Endrass (2013) also identified a list of weaknesses in the standard proposed and even underlined that the data needed for the computation of KPI sometimes is missing and vaguely described[32]. Furthermore, he emphasized that there is lack of guidelines in the standard to set goal and improve performance. Moreover, he recognized that the provision of unique architecture for every kind of individual production process is unrealistic. Also, Kang et al. (2016) proposed a hierarchical structure to categorize KPIs and identify the inherent relationships between them [34]. He figured out a need for introducing KPIs and its supporting elements to be consistent with multistage production system. As a result of weaknesses in IS0 22400, Varisco (2018) proposed a classification model to highlight whether a KPI is related to one or more work units and one or more work or production order. This is a development to resolve the question introduced by Kang et al. (2016) about the applicability of the standard in multistage production environment.

In chapter 4, elements and related key performance indicators are described in detail to calculate and select the key performance indicators for the enterprise under study.

3. METHODOLOGY

3.1 Background:

In this chapter, we will discuss the framework upon which the realization of integration of MES with PLM is carried out in the form of **knowledge Based System**. This Knowledge Based System is a result of symbiosis of DIGEP (Dipartimento di Ingegneria Gestionale e della Produzione) of Politecnico Di Torino and Software Solutions Company.

Knowledge based system framework addresses two major issues. The first one is related to lack of analysis in highly customized and prototypal production, where complex operations and routings make very cumbersome to manage various manufacturing variables without increasing costs and wasting time. The Second problem is related to the formalization of structure associated with the data collection related to the observed anomalies and faults during manufacturing on the shop floor and enabling designers to learn from the mistakes of the past. In such a way, designers can have in depth analysis and provide improvements in the product design, thereby increasing the operational efficiency.

In line with the problems, the proposed framework offers technical innovations like i) open-source architecture for PLM-MES integration through knowledge-based system ii) an advanced data model to relate data between PLM and MES iii) provision of storing of data related to anomalies.

3.2 Proposed Framework of Knowledge Based System

Proposed framework (Knowledge Based System) acts as a bridge between **product design** and **process execution**. The main objective is to reduce the **trial-and-error cycles** by collecting and standardizing the experience breakthrough and reusing the knowledge. Consequently, such companies would not be dependent on tacit knowledge and would have a whole history of different products designed and manufactured and anomalies and problems faced during production.

The proper system is user centric as it will allow to collect the critical realization of components in an organized way, and experience breakthrough developed during the process.

Moreover, reusing the knowledge will help the designers to design and make more robust and reliable models of the product with least errors. The conceptual model of the integrated system

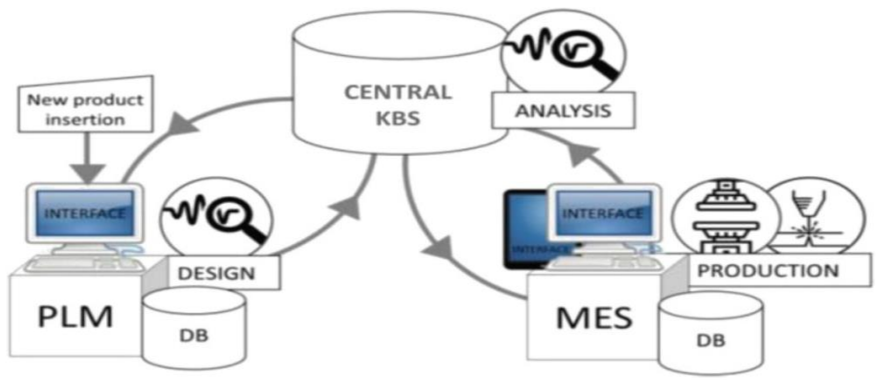

Figure 11: Conceptual model of the integrated system

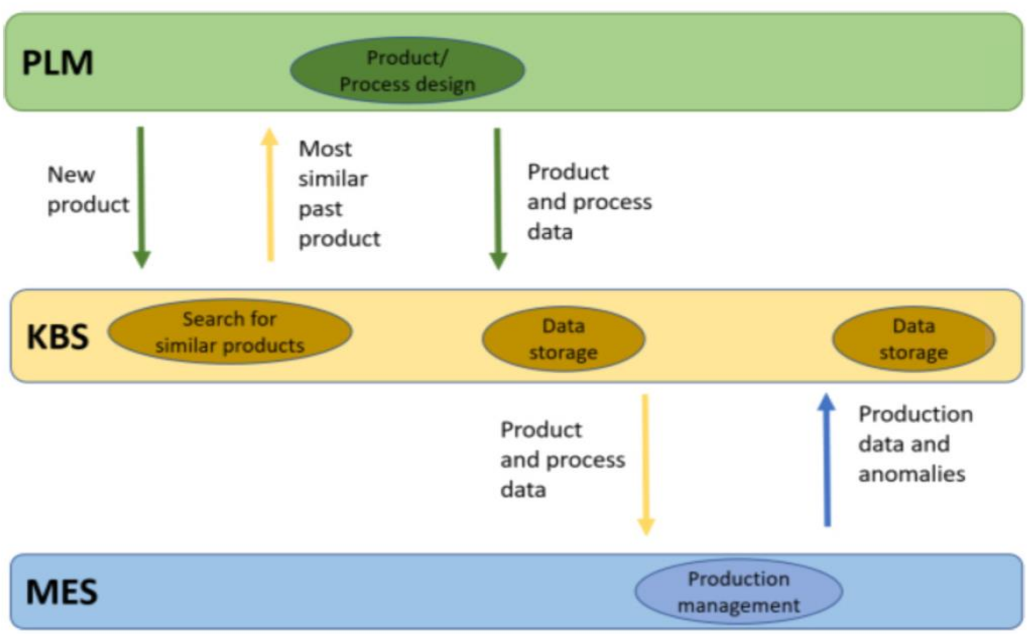

Figure 10: Information flows among PLM, KBS and MES

and information flows among KBS, PLM and MES are shown in the figure 10 and 11. Upon receival of order from the customer end, the company must define the sequence of production activities using its PLM module to manufacture the product. To reduce time, similar products in the database of KBS can be searched for using similarity matrix using similarity metric[35].

To save time, a similar product with respect to the order can be searched in KBS and appropriate changes in the production activities could be applied. After the product is finalized in PLM, it is sent to the KBS (storing the design for future reference) and eventually it gets accessible to MES.

After execution of the processes by MES, it sends information regarding issues encountered during each activity of production. Eventually, appropriate changes are made in the design of production activities in PLM, which are then fed to KBS.

3.2.1 Entity Relationship Model:

Knowledge Based System (KBS) is described using entity-relationship model shown in figure 12, influenced by Core Product Model (CPM), Toronto Virtual Enterprise Ontology Model (TOVE), the ADAptive holonic Control Architecture for distributed manufacturing systems model (ADACOR) and the Almost Perfect Approach to Scheduling. As shown in the diagram, entities with blue color comes from the MES while entities with green color come from PLM. Moreover, there is one entity displayed in yellow (ProjectInformation) which contains information about orders and customers and comes from ERP. Since, in this model ERP is not discussed, we would thus assume entity is also coming from PLM.

Essentially, the starting point of production of a product starts with the receival of order from customer. ProjectInformation task is to collect this information about the product and is directly linked to MaterialInformation- Product. A product is connected to the RouteHeader (Production Cycle) with a relation (1,n) since a product may have one or many production cycles. Whereas a production cycle is unique for a single product. Route header element is acting as an intermediate stage between MaterialInformation Product and RouteOperation. RouteOperation has the corresponding data to manage the ordered operations in the cycle. Route Operation is connected to Operationlist, Machine Model and Operation Resources and with the entities of the MES that control the production cycle. RouteHeader has (1, n) relation with RouteOperation since a production cycle has at least one and many production operations. But one operation is linked to one production cycle at a time.

The entity Operationlist keeps the record of all operations along with their description and codes. It has a relation of (1, n) with RouteOperation since an operation can be linked to one or more sequence of operation. Machine model is the main entity which collects the data about the equipment and machinery. RouteOperation has a (1,1) relation with Machine model as a production operation can only be performed by a machine, whereas a machine model may or may not include a certain type of operation (manual operation). MachineInformation entity is directly linked to the Machine model with (1,1) relationship since every real machine would have an associated model, whereas machine model may have none or many machines associated with it.

The distinction between MachineInformation and Machine model can be made in a way that the former is the responsibility of MES system while the latter is required by PLM system[36]. MES entities ProductionRequest and ProducitonSegment also shares relationship with each other. The order created by former will be planned by the latter entity. Since ProductionRequest

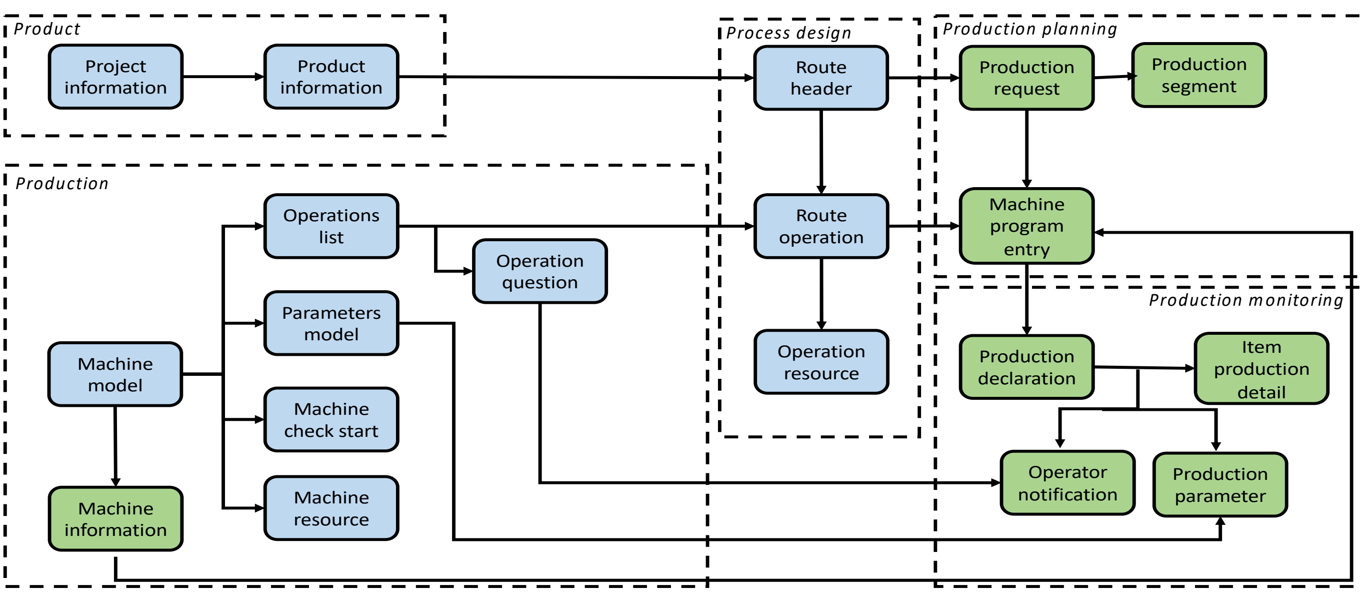

Figure 12: ERD diagram of a generic KBS for a manufacturing company

has multiple orders inside it, so the same order can be made by one or more operations to be planned by Product Segment. However, a planned operation is linked to a single order.

Another important entity coming from PLM is ProductDeclarations because it contains information about the progress of the production. This entity evaluates data entry to machinery one by one. ItemProduction Details evaluates statements saved in the ProductionDeclarations obtaining the status of the articles declared (good, scrap or to be evaluated).

3.2.2 Data Flows in the framework

Data flows can be categorized into smaller and occasional flow and a continuous and larger one. The former is related to the occasional insertion of data e.g., in the event of purchase of new machine different from the rest. The latter flow corresponds to the orders given by the customers and consequent generation of production cycles.

The data flow from MES to PLM is compressed since analyzing the whole production monitoring data directly would be cumbersome for the designer. Therefore, firstly the data is interrogated by the operator about the variant and later it is sent to the PLM.

ARAS which is an open-source PLM software was used to digitalize and store information related to resources of the company and production process of each product. KBS was implemented using PostgreSQL database. The commercial MES software JPiano was used to implement the MES platform.

User interface was developed on ARAS to insert data related to type of machine entity, activities, product, check start and check end. To replicate data from ARAS to MES, a merge replication was implemented. ARAS also gives an opportunity to attach documents related to the production cycle with the help of MES entities like ItemProductionDetails table, data in ProductionParameters, ProductionDecalaration and OpertaionNotifications tables are summarized to give a general overview of process performance.

3.2.3 Case Study and application of Framework:

The company under observation is a tier 2 supplier for a known automotive supplier. Their core competency is development of complex manufacturing processes in short time providing protypes and pre series products. The issue faced by the company is the lack of digitalization of production processes. When the die of design is approved by the responsible person, the role of designer and he does not receive any feedback on possible problems caused by the dies during the production. This lack of bidirectional information hinders continuous learning for both parties. Production process is characterized by different steps. The first step is the delivery of CAD model by the customer needed for production. Upon receival of CAD model, the designers finalize the production process and dies needed for production. After that cutting and pressing operations are used to produce the prototype.

3.2.4. Future Perspective of Proposed Framework

The main objective of the Framework Application is to record the information related to production cycles to minimize the criticalities. Moreover, it is possible to perform a dynamic and historic management of data. As a result, there is an improvement in the information flow between different departments of the company. Similarly, second management of data is associated to the digitization of company know how. In this way, whatever work is performed by technicians in PLM is automatically synchronized and transferred to the MES.

Future works comprise data analysis techniques for using stored data in KBS and a comprehensive integration also considering integration of ERP. This step will enable to get a better overview of enterprise and will support the tactical-strategic decision making. To make this integration possible, outright enterprise system integration (OESI), which grows vertically among company functions and along the product lifecycle would be possible introduced.

3.3 Definition of Tables:

In this section, tables corresponding to various parts of MES and PLM functionality are explained. The codes and data used in this section are in line with the credentials of Italian Car Prototyping Company. As KBS is a symbiosis of MES and PLM, therefore some tables are associated with MES and some with PLM. Mainly, two flows can be observed in the data model as shown in figure 13.

- From PLM module to KBS database to MES module
- From MES module to KBS database to PLM module

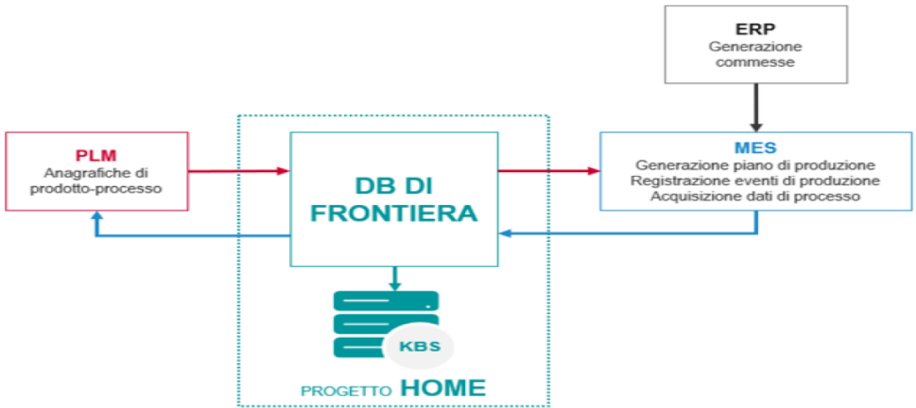

Figure 13: Illustration of data flows among PLM, KBS and ERP

As can be seen in the figure 13, PLM incorporates the data related to product and process requirements. Design engineers formulate the design of the product keeping in mind the process requirements to make its production cost effective and profit yielding. This is undoubtedly the starting point of realization of product and require multiple inputs through various accompanying departments throughout the iterative cycle of product development. The data from PLM becomes accessible to KBS central database which is the meeting point of various attributes of the product and process design with the MES. After KBS, the baton is handed over to MES to include the various attributes related to the production of required products. These attributes include generation of production plan, registering of production events, and acquisition of process data. One important to note in the figure 13 is the one-way flow of input data from ERP about the production orders and commercial project information.

To understand and integrate the fields that need to be evaluated to make a central database, a thorough analysis of the data of PLM and MES was carried out. During the analysis, those flows in the system were observed which carry out the realization of HOME project- a smart connected system based on knowledge reuse and experiential learning

Data in a KBS for a generic manufacturing company can be divided in five macro-categories:

1. **Product data**: contains information regarding products and customer orders.

2. **Production data**: comprises all the resources of the company and the operations that can be executed.
3. **Process design data** contains information of the design of the production cycles for each product.
4. **Production planning data**: assign the operations of production cycles to the resources.
5. **Production monitoring data**: real time monitoring of operations, with starting and finishing times and quality assessment of the produced parts.

3.3.1 Product Data:

This category of tables contains information related to exchange of data related to raw materials, products, and customer orders. For instance, regarding materials, it gives information about finished products, work in progress, raw materials, and molds used from manufacturing. Regarding human resource, it provides information about the persons involved in production, management of people, their shifts, their workloads etc. In the original HOME project, data about semi finished and final products is not considered for the sake of simplicity.

3.3.1.1 ProjectInformation (ERP):

This entity, originally coming from ERP, contains information about the customer's orders. But in our case since we are not considering ERP integration, we would assume it to be coming from PLM. Customer field contains the name of the customer. Description field describes the description of the project under development. Similarly, other details such as CustomerReuqestDate and CustomerRequestID refer to the date of order placement and client's or der code. Quantity field signifies the number of products to be made. ExternalDocument ID corresponds to the external report ID about the project. EarlistStartTime refes to the earliest start of production of the project. Finally, ReasonType refers to the type of project under development.

Column Name	Description
ID	Order number
Customer	Customer name
Description	Project description
CustomerRequestDate	Date of order
CustomerRequestID	Customer order ID
Quantity	Quantity requested
Duration	Expected duration
ExternalDocumentID	External reference
EarliestStartTime	Requested starting time
ReasonType	Project typology

Table 4: : ProjectInformation

3.3.1.2 MaterialInformation/ProductInformation (PLM):

This table belonging to PLM contains information related to products, raw materials, and tools. Starting from the type of material used in production, it gives information about unit of measurement of that material, quantity of pallets of that item, type and class of material, base material, family, subfamily etc. Type of material corresponds to the classification of material as a tool or material to be used during production. Base material refers to the basic material used to produce the tool or raw material and it contains the code given by ERP. Materialdefinitionidtype field in this table specifies the type of instrument (ST per mould, PT per pallet, ...). Moreover, In the case of molds, we have the coding for the type of material made explicit in Basematerial, while in Subfamily we have the type of operation carried out by this mold. Semi-finished products are recorded each time they are stored in warehouses and not at the end of each operation.

Here, one point to note is raw material refers to discrete items such as sheets; liquids such as oils and assembled products like molds used for forming and stamping. Route code is used for the integration of production cycle during assembly. Moreover, link to a CAD file and date of entry of material in the system are also added in the table for user reference.

Column Name	*Description*
ID	Item code
Description	Item description
UnitOfMeasure	Standard unit of measure
PalletQuantity	Standard pallet quantity
PublishedDate	Creation date
MaterialClass	Item typology (FP, RM,SF, TOOL)
MaterialDefinitionIDType	External item typology
BaseMaterial	Base material code
Family	Family ID
Subfamily	Subfamily ID
Complexity	Product complexity
CycleQuantity	Product quantity per cycle
CADFile	CAD link
RouteCode	Production cycle code

Table 5: ProductInformation

3.3.2 Production Data:

3.3.2.1. MachineModel (PLM):

It is the most important table of our Knowledge based system, as it refers to the types of machines available for manufacturing at plant. As apparent, every machined model has a unique ID corresponding to the type of operation carried out by that machine. Description refers to type of operations carried out by the machine. Moreover, other fields like Family and subfamily refer to machine type and subtype. OtherParameter and OtherParameterName refer to some other specifications worth mentioning related to the process, for instance, flow rate of the liquid and plateau size for presses.

Column Name	***Description***
ID	Model code
Description	Function description
Family	Machine type
Subfamily	Machine subtype
OtherParameter	Family parameter
OtherParameterName	Family parameter name
Note	Additional notes

Table 6: Machine Model

3.3.2.2 OperationsList (PLM):

Another important table in production data is OperationList. This table include data related to all type of operations carried out in the company. Each type of operation has a unique ID just like machine mode. Interestingly, this table follows a similar fashion in a way that the Description field contain the overall description of the operation and TypeCode, TypeDescription and ProcessCode are further classification of operation. For instance, if the company wants to carry out the **2D LASER CUTTING ON PLATINUM** with ID '**10L1**', then fields are divided in this way: TypeCode (10), TypeDescription(Sheet metal preparation), ProcessCode (L1).

Column Name	***Description***
ID	Operation code
Description	Activity description
TypeCode	Operation type code
TypeDescription	Operation type description
ProcessCode	ID related parameter

Table 7: OperationList

3.3.2.3 OperationQuestions (PLM):

For each operation, some closed-ended questions are provided by the PLM to be answered later if you want to report a problem. For the moment, our system remains on binary answer questions. Here OperationID corresponds to the type of operation being carried out on the material. In fact, this field is coming from OperationList table which displays all possible operations and processes performed in the company. Question fields asks the question about the problem carried out during operation. For example, it could be something like ‘does the material have molding problems?’.

Column Name	***Description***
ID	Unique code
OperationID	Operations list ID
Question	Question text

Table 8:OperaionQuestions

3.3.2.4 ParametersModel(PLM):

This table contains information about the parameter values from which an operator can choose parameter value for the machine depending on the operation. Generally, each parameter has a unique ID field followed by the description of the parameter, for instance, press pressure, velocity of stamping etc. One important field in this table is Machinemodel ID, which connects

Column Name	***Description***
ID	Parameter code
Description	Parameter description
MachineModel	Machine model ID
ValueType	Parameter type
MinValue	Minimu value
MaxValue	Maximum value

Table 9: Parameters Model

ParameterModel table with the MachineModel table. ValueType talks about the type of parameter we are entering for the machine. Lastly, MinValue and MaxValue correspond to the minimum and maximum value of the parameter under discussion.

3.3.2.5 PersonnellInformation (MES):

This table contains information about human resource working at the plant. Every person has a unique ID field through which that person can be accessed in the data base. Description refers to the name of operator, work center indicates the location in the plant, SerialNumber and BadgeCode refer to the number associated with the employee and last not the least, role gives information about the position of the person in the company (operator, foreman, manger).

Column Name	***Description***
ID	Operator ID
Description	Operator Name
Workcenter	Location of Work
SerialNumber	Serial Number of Operator
BadgeCode	Operator Badge Code
Role	Designation of Operator

Table 10: Personnel Information

3.3.2.6 MachineCheckStart (PLM):

This table contains information about the necessary checks to be carried out on the machine before an operation on that machine is performed. Again, MachineModel ID field is used to synchronize the machine upon which the operation is to be carried out. Resource code refers to the raw material being used for the operation. It can be added, as necessary. Lastly, CheckStart is a field which implies the description of the check to be looked upon during the operation. For example, verification of correct cutting parameters, correct sheet metal positioning parameter, check for sheet metal presence in pallet etc.

Column Name	*Description*
ID	Unique code
MachineModel	Machine model ID
Resource	Resource code
CheckStart	Check description

Table 11: MachineStart

3.3.2.7 MachineInformation (MES):

This table is of empirical importance in the domain of operation management. It includes information on the physical machines present in the department. Theoretically It is an object of ERP department since it contains plant level information but, in our project, we consider it in MES. Every machine setting has a unique ID followed by its work center location. This table is connected to the machine model to have a bilateral communication about important fields. Description tells us about the name of the machine being used for the operation. Similarly, technological level asks the user about the complexity level of the machine. Moreover, we also have fields related to the size and dimension of the machine. For instance, for Emanuel (Benelli) hydraulic press machine the dimensions of the machine are: 8000 X 3000.

Column Name	*Description*
ID	Machine code
WorkCenter	Workcenter name
MachineModel	Machine model ID
Description	Machine description
TechnologicalLevel	Machine technological level
MachineSize1	Machine first dimension (width)
MachineSize2	Machine second dimension (length)
Note	Additional notes

Table 12: MachineInformation

3.3.3 Process Design:

3.3.3.1 Operation Resource (PLM):

This table refers to resources used in each operation. Sequence field includes the necessary check that should be taken before starting the operation. Description field is a verbal description of type of resource (material, tool) needed to perform the operation on the equipment to get the product. One important point to mention here is Product ID which is an ID field from ProductInformation table. Operation code field is a combination of route code and operation list. It gives information about the type of operation needed to make the product and the cycle it is following. Resource code corresponds to actual code used for the operation (equipment, tool) and it is originally a unique ID in ProductInformation table. For example, 'NYLONSTAMP00' is code meaning 'nylon required for stamping'. Use rate is a coefficient of use of a specific resource.

Column Name	***Description***
ID	Unique code
Sequence	Check before the operation
Description	Resource description
Product	Product information ID
OperationCode	Cycle operation code
Resource	Resource code

Table 13: OperationResource

3.3.3.2 RouteHeader (PLM):

This table contains information about the production cycles related to product and each product can be associated with more than one production cycle due to the revisions. The production cycle consists of an ordered list of operations to be executed to obtain a product. ID of this table is the combination of three instances: Product ID, 'K' letter and revision number. Description tells us about the details of the production cycle. Product in this table is a field imported from the ID of ProductInformation table (product). In this way, the product to be manufactured can be monitored over its production cycle. Revision field corresponds to the number of revisions, the product has required during its entire production cycle. Duration is expressed in hours and an estimate is made considering the entire setup time for each machine.

Column Name	***Description***
ID	Unique code
Description	Description of product cycle
Product	Product code
Revision	Revision code
Duration	Duration expressed in hours

Table 14: RouteHeader

3.3.3.3 RouteOperation (PLM):

This table contains information about all the operations carried out in each cycle. It lists the sequence of operations needed to define the production of a product. This is one of the most important table of the framework, as multiple ID fields from other tables are converging to it. Route Code is the ID field of RouteHeader which tells us about the revision of product being manufactured. Sequence field corresponds to the operation number being carried out by the machine. Operation field is the key field of OperationList table which refers to type of operation carried out on the work piece. e.g. 2D laser cutting. Machine model, as we have already seen in other tables as work, is the ID field of MachineModel table, which tells us about the family and

Column Name	***Description***
ID	Operation ID
RouteCode	Route ID
Sequence	Operation sequence
Operation	Operation code
MachineModel	Machine model ID
ToolingTime	Setup Time
WorkingTime	Working time (expected)

Table 15: RouteOperation

type of machine we are using for production. Tooling time and working time as apparent refer to the setup time and operation time on the workpiece.

3.3.4 Production Planning Data:

This section of data model contains information related to the planned production cycle for the production orders.

3.3.4.1 ProductionRequest:

This table associate different production cycles to customers' orders specifying for each cycle the quantity to be produced and the estimated duration of the operations, as well as other parameters. The key field of this table corresponds to the order number for production. Description field explains the secondary orders produced as the result of subdivision of an order coming from RouteHeader entity. Product field is the key field of ProductInformation table giving information about the product to be produced. Project entity is the ID field of ProjectInformation table generated from ERP entailing all the information about the product. Priority field sets the priority of sub orders to be manufactured. Another important mention here is RouteCode which is the ID field of RouteHeader data. The breakdown of materials needed for manufacturing a product is given by Bill of Materias field.

Column Name	***Description***
ID	Manufacturing order number
Description	Order description
Product	Product code
Project	Project reference
Priority	Sequence priority
Quantity	Requested quantity
EarliestStartDate	Requested start date
LatestEndDate	Requested end date
Duration	Request duration
RouteCode	Production cycle code
BillOfMaterial	Materials detail

Table 16: ProducionRequest

3.3.4.2 ProductionSegment (MES):

This table contains data that manages the planning of individual operations of the cycle related to a particular order. In this way, it reports for each operation of production cycle the assigned machine, the estimated duration, the earliest start date, and the latest end date. As apparent in the table, ProductionRequestID is the key field of ProductionRequest table which is explained earlier. ProductionSegmentSequence defines the sequence of operations needed to completer the product. It is the same field as observed in RouteOperation table. Similarly, ProductionSegmentID which is the key field of OperationList table is the operation code of the production cycle for a product. Machine field represents the tag of the machine on which the operation is carried out. Cycle quantity tells us about the number of products being manufactured in one cycle. Other fields in this table have already been explained previously.

Column Name	***Description***
ID	Operation ID
ProductionRequestID	Manufacturing order number
ProductionSegmentSequence	Production sequence code
ProductionSegmentID	Operation code
Quantity	Requested quantity
EarliestStartDate	Requested start date
LatestStartDate	Requested end date
Machine	Machine code
Priority	Sequence priority
ToolingTime	Tooling time (actual)
WorkingTime	Working time (actual)
CycleQuantity	Quantity per cycle

Table 17: ProductionSegment

3.3.4.3 MachineProgramEntry (MES):

It associates the schedule of operations to each machine, with the planned start and end time. Just like ProductionSegment, this table also manages the single operation of the production cycle for the manufacturing of desired product. Machine field refers to the key field of MachineInformation table. Similarly, just like previous tables, this table also include the product field, which is basically the key field of ProductlInformation table. As evident, ProducitonRequestID is the key field of ProductionRequest table. Moreover, here, operation field is corresponding to the key field of RouteOperation table which line up the sequence of operations to define the production cycle. Description field tells us about the type of operation carried out by the machine. Priority field lists the priority of activities during the production cycle. SchedStart and SchedEnd enlists the start and end of schedule of production cycle.

Column Name	***Description***
ID	Program code
Machine	Machine information ID
Product	Material information ID
ProductionRequestID	ProductionRequest ID
Operation	Route operation ID
Description	Operation description
Priority	Sequence priority
SchedStart	Scheduled starting date
SchedEnd	Scheduled end date

Table 18: MachineProgramEntry

3.3.5 Production Monitoring:

This is the last section of our database. Essentially, the reason behind making this table is to collect the data from MES and disseminate this data to Knowledge Based System. It has multifold benefits. Firstly, it will make possible to monitor the progress of data during production. Secondly it will allow to receive various production feedbacks from operators and line men (machine failure, defected lot, improvement of system etc.).

3.3.5.1 ProductionDeclarations (MES):

It represents the **actual duration** of the operations on the machines, categorizing setup and eventual downtimes and the corresponding reasons; here, quantity of good and discarded parts is also reported. This table contains information related to the progress of production. It has a lot of fields that are the key fields of other tables. ProductioRequestID is the ID field of ProduductionRequestID table. Moreover, ProductionSegmentSequence gives the sequence of operations in which the final product is manufactured. Personnel ID field comes from the PersonnelInformation table giving all the details about the workers in the company. Data of machine on which the activity is carried out is of empirical importance. Therefore, we also included the field of machine in this table which is the key field of MachineModel table. To check the items that are declared good and defective, we have added GoodsQuantity and ScrapQuantity fields. Record type refers to the time when the observation is made, for instance, it could be during the running time, setup time and idle time of the machine. ReasonCode field is basically the cause of the problem. E.g., modification of laser parameters, pressure parameter,

Column Name	***Description***
ID	Operation ID
MachineProgramItem	ID field of MachineProgramEntry table
ProductionRequestID	Production request ID
ProductionSegmentSequence	Cycle sequence
PersonnelID	Operator code
Machine	Machine code
GoodsQuantity	Quantity of good products
ScrapQuanity	Quantity of scrap products
DateFrom	Starting time
DateTo	Finish time
Time	Total time
RecordType	Type of record (working, setup, block)
ReasonCode	Reason for the record type
Annotation	Notes
SegmentCompleted	Order status (closed, opened, aborted)
Attachment	External file ID

Table 19: ProductDeclarations

changes to the pallet etc. Annotation corresponds to detailed information of the recorded event. Segment completed field refers to the state of order during which the observation is made. In the Attachement field, a worker can upload a picture or multimedia file of the problem observed.

3.3.5.2 Attachment (MES):

This table is meant to handle the multimedia files (such as photos and videos) attached during the observation taken during the production cycle. It has two only fields: 1) ID field 2) field containing the link of the file attached.

Column Name	***Description***
ID	Attachement ID
Link	Link of attachment

Table 20: Attachment

3.3.5.3 ItemProductionDetails (MES):

Reports all the discharged parts of an operation, specifying quantity discarded, the machine and the reason of the discard. This table contain information about the production status of a set of products. The function of this entity is to evaluate the records stored in the ProductionDeclarations table every certain interval. As a result, this entity declares the status of

Column Name	***Description***
ID	Unique code
SessionID	Production declarations ID
Quantity	Declared quantity
Result	Item status
SerialNumber	Item code
PersonnelID	Personnel information ID
Machine	Machine information ID
Annotation	Operator notes
Parameters	Machine parameters ID
Attachment	External file ID
NotificationDate	Date

Table 21: ItemProdcutionDetails

the articles: good, scrap, or to be evaluated. SessionID field is the key field of ProductionDeclarartions table, thereby linking these two tables for data dissemination. Quantity refers to the number of items declared good or scrap. SerialNumber corresponds to the serial number of the item whose status is declared. It is only written if the quantity of the item is one, otherwise left blank. PersonnelID field appearing here is the same field we saw in PersonnelInforamtion table. It provides information about the person who is taking the observation. Machine field like in other tables correspond to machine code of the machine stored in the machine model of the framework. Observation noted by the operator is written in the annotation field. Parameter setting during the production of a subset of order is carried out by Parameters field which we know is also the key field of Parameters model table.

3.3.5.4 OperatorsNotifications (MES):

This table reports the answers to questions defined in the OperationQuestions table during the execution of operations on each machine. DeclarationID is linking this this table to ItemProductionDetails table to get the status of the product being manufactured. QuestionID refers to the key field of OperationQuestions table which lists down the main question that could be asked during the production. For now, for simplicity we are assuming it to binary.

Column Name	***Description***
ID	Unique code
DeclarationID	Item production details ID
QuestionID	Operation question ID
Answer	Binary input

Table 22: OperatorsNotifications

3.3.5.5 ProductionParameters:

This table reports the values of the parameters set in each machine for each executed operation. The most important aspect of customized or made to order production is the parameter setting of the machine. Minute changes of the parameters in the model can have major changes in the desired product. That is why we also made a table for this reason called ProductionParameters. In line with the model, we have two foreign key fields in this table. The first one is

DeclarationID, which is the key field coming from ItemProductionDetails and ParamterID, which is the key field of ParametersModel table.

Column Name	***Description***
ID	Unique code
DeclarationID	Item production details ID
ParameterID	Parameters model ID
Value	Preset value

Table 23: ProductionParameters

4. APPLICATION

4.1 PROJECT BACKGROUND:

This thesis is written as a part of HOME (**Hierarchical Open Manufacturing Europe**) project for EURODIES S.R.L- a company specializing in rapid prototyping and sheet metal components. HOME research project is based on digital transformation of production into interconnected system under the industry 4.0 regime. The HOME research project of Piedmont region is financed with European funds and aims at the exploration and development of industry 4.0 production model. It includes 27 partners: nine technological development companies, nine industrial companies, and nine research institutes (including Politecnico DI Torino). HOME envisages factory as a single large machine, equipped with state-of-the-art information systems and open architecture. The overall goal of this project is to improve use of resources, enhance maintenance and operational performance, increase traceability, and help in monitoring critical issues in real time. As a result, an organic environment comes into existence where decisions taker is faster and based on complete and integrated data. The used of information systems for better data utilization has become a reality with the invent of Industry 4.0. The use of digital monitoring and control systems, smart instruments, web-based applications, machine learning, and big data has transformed traditional factories into smart factories. The use of cyber -physical -production-system (CPPS): intelligence, connectedness, and responsiveness[37] enable the interaction of digital technology with physical environment in a smart factory. The use of smart factories would streamline the data flow and interaction between different levels of functional hierarchy proposed in IEC 62264-3[5].

This thesis analyzes a framework in which integration of Manufacturing know how management system with Product Lifecycle Management has been done. This framework came into existence as result of collaboration between DIGEP (Dipartimento di Ingegneria Gestionale e della Produzione) of Politecnico Di Torino and AEC Soluzioni SRL, Torino. AEC Soluzioni, founded in 2013, is a software solution provider which specializes in smart and integrated solutions for manufacturing companies. Their core competencies revolve around the realization of industry

[5] https://www.iso.org/standard/57308.html

4.0 regime, automation, integrated factories, and big data. Their worth mentioning development is JPiano Software which is an MES software dealing with integrated manufacturing planning, smart notification system, technology integration, traceability management, energy saving and much more.

The choice of metrics and performance indicators is crucial to assess the success and the effectiveness of the integration process. In fact, maintaining consistency between defined key performance indicators and medium-long strategic objectives is imperative. In this chapter, we will formulate and put light on the acquisition of most essential and effective key performance indicators prevalent in the manufacturing industries. For this help would be taken from published and on-going research based on the effectiveness of KPI in manufacturing setting. One point to note is, we must tailor the KPIs according to the needs of stakeholders involved in the project. That means we must wisely select and choose the indicators which is best suited for our client.

The concept of KPI and associated aspects such as its characterization, types and selection criteria has already been explained in second chapter. Now we define the elements in the context of MOM needed for the calculation of KPI and ultimately after defining various KPIs, we select the most appropriate KPI useful for medium size enterprises.

4.2 Elements for KPIs Measurement:

Elements are the basic measurements and observations directly associated to the process or activity related to the production. In fact, elements are the entities that act as building blocks for the generation of the KPIs. This is because elements are responsible for the direct measurement of the production activity whose performance needs to be improved. For instance, Actual unit busy time (AUBT) is an element which refers to the actual time that a work unit is used for the execution of a production order and similarly actual order execution time refers to the execution time of production order.

Essentially, after getting concept of elements, lets dive into the scope of work in which the elements for KPI computation can be used. This concept is precisely depicted in the role-based equipment hierarchy proposed by IEC 62264-3. This standard proposes a hierarchical structure for the physical equipment used in the manufacturing plants (see Figure 14). The hierarchical model starts with the enterprise- largest entity that may include multiple sites and plants. Then comes the site or plant which may contain multiple production areas related to different products. At bottom level comes the most important entities responsible for the measurement of process metrics.

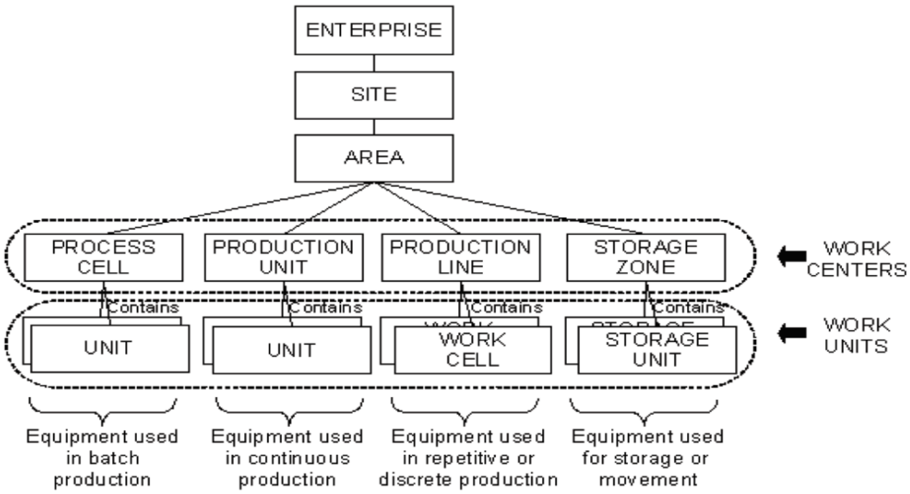

Figure 14: Role based equipment hierarchy [38]

It starts with the process cell which contains equipment for batch production. Process cell is followed by produciton unit which contains equipment used in continuous produciton. Later comes the work cell which contains equipment used in repetitive or discrete production. Last but the not the least is the storage unit containing equipment for the storage of produts. This hierarchical diagram represent the most descriptive segragation of KPI elements in terms of their level of applicablility.

As in our case, we are focussing on MES (Manufacturing execution System) which is third level of functional hierachy, so we are intersted in identifying and selecting KPIs for this level. MOM sometimes refer to MES models four major categories of oeprations manaemet: production operations management, maintenenca operations managemnt, quality operations management, and inventory operations mangement.

By now, we are familiar with the concepts, description and structure of KPIs and its elements. To better visualize KPIs and their relationships with the elements, different models have been introduced and explained in ISO 22400. One of them is effect model diagram which is a graphical representation of the dependicies of the KPI elemetns that is useful for understanding the impact of the source values. For understanding effect model diagram of quality ratio is taken from ISO 22400-2 is shown figure 15 [38].

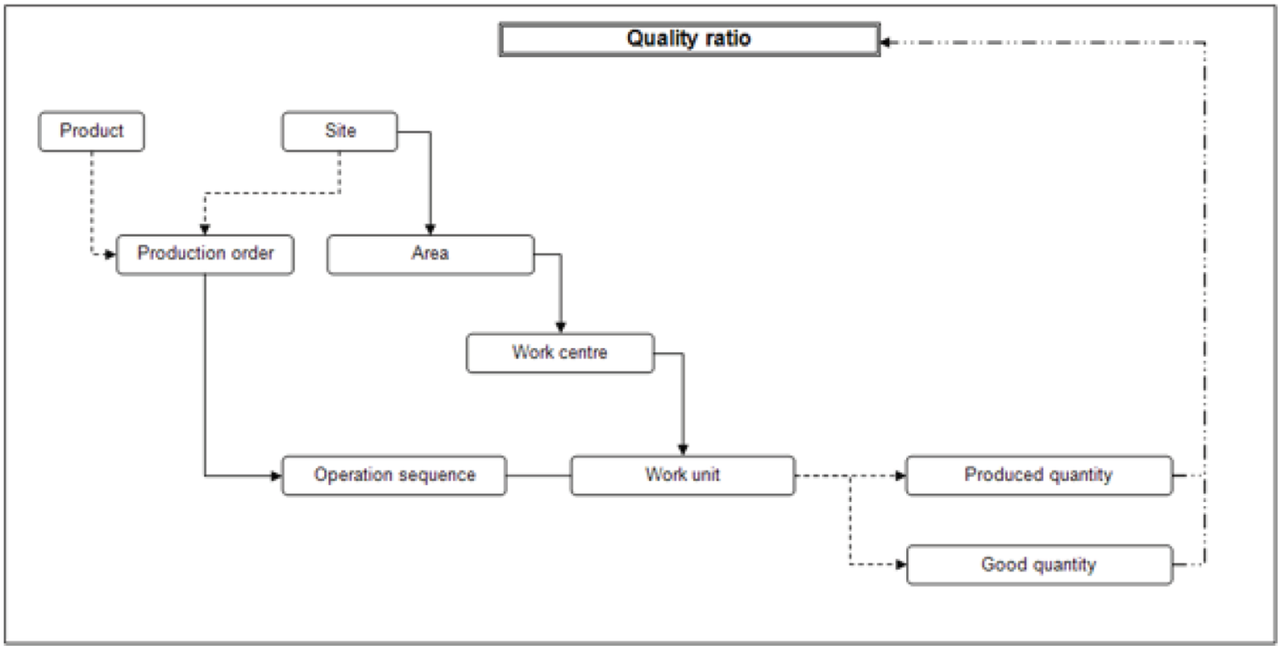

Figure 15: Effect model diagram of Quality Ratio [38]

In this effect model diagram the relationships between KPI ‘Quality Ratio’ and its constituent elements are shown. The model starts with the highest entity product for which production order is generated as its constituent part. Similarly, the relationship between Site, area, work center and last but not the least work unit is displayed by the ownership relation (solid arrow). Moreover, to join operation sequence with the work unit we are using one to one relationship since a particular operation sequence is associated with the specific work unit. Ultimately, we reach the level of defining the elements ‘produced quantity’ and ‘good quantity’, which will consequently give us the KPI ‘Quality Ratio’.

4.3 Descriptions of KPI Elements:

After analyzing the various aspects of Key Performance indicators and their application in the manufacturing industry, let us put some light on the relevant measures or elements that help us to understand and compute the Key performance indicators. Although, ISO 22400-2 tried to describe the elements related to time, quality, energy, and maintenance functions in detail, but the terms and definition used are unclear and vague. There is a need for the refinement and modification in some of the definitions of elements provided by ISO 22400-2. The elements can be broadly classified as follows:

4.3.1 Time Elements:

The time elements are the measurements related to time durations in production system operations and they describe activities related to production and maintenance functions. In production domain, these metrics can be measured from the point of view of a production order, work unit or operator [34].

4.3.1.1 Planned Times:

From a machine or work unit point of view, we have the following time elements[34]:

- *Planned Operation Time (POT):*

Referring to machine or work center, this element is defined as the scheduled time during which a machine can be utilized. It can be calculated by adding Planned Busy Time (PBT) and PDOT (Planned Down time).

$$\mathbf{POT = PBT + PDOT}$$

- *Planned Busy Time (PBT):*

It is defined as the time during which a work unit or machine is busy. It can be computed by subtracting the planned down time from planned operation time.

The two time periods explained above are not the same due to the presence of scheduled non-working time in planned operation time. Therefore, to resolve this issue, planned down time (PDOT) is introduced.

- *Planned Down Time:*

It is defined as the time during which the machine cannot produce. It may include activities related to planned breaks and maintenance.

- *Planned Unit Setup Time (PUST):*

This time element is planned time required for setting up the work unit or machine for a work order.

Now from a production order point of view, we define the following elements:

- *Planned Run time per Item (PRI):*

It is defined as the time to produce one work piece or item of a work order.

- *Planned unit setup time:*

It is the time required to setup a machine for a work order.

- *Planned Order Execution Time (POET):*

This element as the name suggests is basically the planned time for order execution. It includes the planned run time per item (PRI) multiplied by produced quantity (PQ) and setup time (PUST) of the work units. It can be calculated as follows:

$$\mathbf{POET = PRI \cdot PQ + PUST}$$

4.3.1.2 Actual Times:

Planned times might not necessarily be equal to the actual or observed times during production due to malfunctions or breakdowns, line balancing issues and unplanned stoppage. Hence, actual times related to production order on a work unit or machine are defined below to facilitate understanding:

- *Actual Production Time (APT):*

It is a time during which the machine is working on an work piece for an order and that only includes the value adding operation.

- *Actual Unit Setup Time (AUST):*

The time needed to prepare or set up a machine for a work order.

- *Actual Unit Processing Time (AUPT):*

The time required for production and set up of the machine executing the production order. It is given as:

$$AUPT = APT + AUST$$

- *Actual Down Time (ADOT):*

The actual time during which is production is halted due to unplanned malfunctions caused by machinery failures, line stoppages and other unplanned events.

- *Actual Unit Idle Time:*

The actual time the work unit is not working on the order even it is available. This time is *also referred to as actual unit delay time (ADET).*

- *Actual Unit Busy Time:*

This is the actual time during which the machine is executing a work order. It can be represented as follows:

$$AUBT = AUPT + ADOT$$

During the completion of a work order, there may be a need to load or unload the part and that part might have to wait in a buffer or on a next machine in an operation sequence[34]. Such times are defined as follows:

- *Actual transportation time (ATT):*

It is defined as the time utilized in transporting the parts on or between the machines. It can be understood as loading or unloading time the machines.

- *Actual Queuing Time (AQT):*

The actual time in which the material is either in transport or progressing through a manufacturing process i.e. the material is waiting for the process to begin.[38]

- *Actual Order Execution Time:*

This element is defined as the time difference between start and end time of a production order. It includes the actual busy time, the actual transport and actual queuing time. Given as:

$$\mathbf{AOET = AUBT + ATT + AQT + ADET}$$

Similarly, from an operator or worker point of view, we can define the following time elements:

- *Actual Personnel Attendance Time (APAT):*

It is defined as the time a worker is available to work on production orders. It is the difference between login and logout excluding breaks [38].

- *Actual Personnel Work Time:*

It is defined as the time a worker needs for the execution of the production order[38].

4.3.2 Maintenance Elements:

These elements are related to activities related to repair and maintenance of machines. Some important maintenance elements are defined or modified below:

- *Time to Failure:*

It is the time during which a work unit can produce, starting from the completion of a maintenance or repair activity until a new failure occurs on the same work unit. This element is called time between failure.

- *Operating time between failures:*

The actual unit production time between two consecutive failure of a machine[38]. The difference between TTF and OTBF is that TTF also includes unit idle time and setup time.

$$\mathbf{TTF = TBF = OTBF + ADET + AUST}$$

- *Time to Repair (TTR):*

The actual time during which the work unit is not available for production. i.e., under maintenance or repair activity.

- *Failure Event Count (FE):*

This element maintains a record that counts the number of times a machine stops operation due to some fault in a specified interval of time.

- *Corrective Maintenance Time (CMT):*

This is defined as the time spent to repair a machine after a failure or malfunctions occurs during production.

- *Preventive Maintenance Time:*

This is defined as the part of maintenance time during which the preventive maintenance is performed on the machine[34].

4.3.3 Logistical or Quantity Elements:

In this section, logistical elements (as referred in ISO 22400-2) are discussed describing issues related to product quantity and quality.

- *Good Quantity (GQ):*

This is the quantity produced that meets the quality standards.

- *Scrap Quantity (SQ:*

The produced quantity does not meet quality standards and has to be marked as scrapped.

- *Planed Scrap Quantity (PSQ):*

It is the planned quantity of products that are expected to be scrapped when producing the product.

- *Rework Quantity (RQ):*

The quantity that fails to meet the quality standards but can meet these standards by reprocessing[34].

- *Produced Quantity (PQ):*

It is the quantity a work unit has produced with respect to the production order

- *Planned Order Quantity (POQ):*

This quantity refers to the planned quantity of the products to be manufactured for a production order (lot size, batch size).

- *Raw Materials (RM):*

The materials that are converted into finished goods at the end of production fall into this element.

- *Raw Materials Inventory:*

This element refers to the inventory of materials that are to be converted into intermediates and finished goods during production.

- *Finished goods Inventory (RMI):*

This element refers to the final product received at the end of production that meets the quality standards and ready for delivery.

- *Consumable Inventory (CI):*

The consumable inventory shall be material which is transformed in quantity and quality during the production process and which is no longer available for use in production operations [38].

- *Production Loss (PL):*

It is defined as the quantity lost during production and calculated as the difference of output and input.

- *Storage and Transportation Loss (STL):*

This element identifies to the quantity wasted during storing the material in the warehouse or transporting the products from one place to the other.

- *Equipment Production Capacity:*

It is the maximum production capacity of the machine or equipment involved in production.

4.3.4 Quality Elements:

These elements are related to the quality aspects of production such as good parts, inspected parts upper and lower specification limit.

- *Good Part:*

A good part shall be the count of individual identifiable parts, e.g., by serialization, which meets the quality requirements[34]

- *Inspected Part:*

An inspected part shall be the count of individual identifiable parts, e.g. by serialization, which was tested against the quality requirements[34].

- *Upper specification Limit:*

This element is a part of quality perspective and it a value below which the performance of a product or process in acceptable.

- *Lower Specification Limit:*

It is the value above which the performance of a product or process is acceptable.

4.3.5 Energy Elements:

- *Actual Direct Energy Consumption (ADEC):*

It is defined as the actual energy consumption during actual busy time of the work unit.

➢ *Planned Direct Energy Consumption:*

This metric calculates the average energy consumption of the work unit during production of a single product.

Here almost all the elements explained in the ISO 22400 are explained in detail. But in our case, as we are dealing with discrete custom order manufacturing, we will only be using only few of the elements. Now as we have sound understanding about the elements or measures needed to compute the key performance indicators, we can define them.

4.4 Description of Key Performance Indicators:

One of the most relevant KPIs and after that we will try to choose KPIs based on our model. As we our dealing with discrete manufacturing, so our focus would be more on the KPIs related to discrete manufacturing. Where IS0 22400-2 describes the content and context of key performance indictors[38], ISO 22400-3 describes in detail the formula and computation of Key Performance Indicators from their elements[39]. Some of the useful KPIs are following:

4.4.1 Worker Efficiency:

The work efficiency is a metric defining the relationship between Actual Personnel Work Time (APWT) related to production orders and the actual personnel attendance time (APAT) of the employee. Special attention should be given while calculating this KPI as the worker may be working on several work units or production orders simultaneously. It is represented by the formula:

Work Efficiency = APWT/APAT

4.4.2 Allocation Ratio:

It is metric that defines a relationship between actual busy time over all work units (∑AUBT) involved in a production order and actual order execution time of a production order (AOET)[38]. This KPI determines the throughput time caused by the actual processing of a production order because delays increase the throughput time of the production. It is represented by the following formula:

Allocation ratio = ΣAUBT / AOET

4.4.3 Throughput Rate:

Throughput rate is defined as the ratio of Produced quantity of an order (PQ) and the actual order execution time. As apparent by the definition, more the rate is, more productive is our manufacturing. This rate can be recorded on demand and periodically. The goal behind measuring the throughput rate is to identify and minimize the weakest links in production[6]. This indicator is calculated per order after order closing[38]. It is represented by the following formula:

Throughput rate = PQ/AOET

4.4.4 Allocation Efficiency:

This KPI is defined as the actual usage and availability of the planned capacity of a machine, which is measured by the ratio of actual unit busy time AUBT to planned unit busy time (PBT)[34]. This indicator indicates how well the planned capacity of a work unit is used and how much capacity for production is available. It is given by the formula:

Allocation efficiency = AUBT / PBT

4.4.5 Utilization Efficiency:

It is the ratio between actual production time (APT) and the actual unit busy time (AUBT). This KPI can be recorded periodically, on-demand and in real time depending on the requirement. This indicator reflects the productivity of the work unit used for production. Since busy time of

6 https://www.investopedia.com/terms/t/throughput.asp#:~:text=Throughput%20is%20a%20term%20used,links%20in%20the%20production%20process.

the unit is the time when it is adding value to the production, this metric can significantly increase the production volume. It is given by the following formula:

Utilization efficiency = APT / AUBT

4.4.6 Overall Equipment Effectiveness (OEE):

This KPI is especially famous in manufacturing industry since it is a combination of three KPIs: availability, effectiveness, and quality ratio. It gives the percentage of manufacturing time that is truly productive7. A OEE score of 100% means a company is producing only good parts, with no stop time and as fast as possible. If the company's aim is to improve productivity of manufacturing equipment, identifying losses, or benchmarking performance, then OEE is the right KPI for that company. This index is represented by the following formula:

OEE index = Availability * Effectiveness * Quality ratio

4.4.7 Net Equipment Effectiveness (NEE):

The net equipment effectiveness (NEE) index is a derived indicator which combines the ratio between actual unit processing time (AUPT) and planned busy time (PBT), the effectiveness KPI and the quality ratio into a single indicator[38]. NEE is comparable to OEE, but NEE includes a modified formula for availability KPI given by the ratio of actual unit busy time to planned busy time. The KPI is given by the following formula:

NEE index = AUPT / PBT * Effectiveness * Quality ratio

4.4.8 Availability:

[7] https://www.oee.com/

This indicator is also related to the capacity of the work unit used for production. It shows a relationship between actual production time (APT) and planned busy time (PBT) for a work unit. Availability index demonstrates the available capacity of the work unit against its utilized capacity. The data related to the availability of the work unit can be collected on-demand or periodically. It is given by the following formula:

Availability = APT / PBT

4.4.9 Effectiveness:

It defines a relationship between planned target cycle and actual cycle expressed as the ratio of product of planned runtime per item (PRI) and the produced quantity (PQ) to actual production time (APT). Higher the result of the ratio, higher the effectiveness. It can be recorded in multiple ways: on-demand, periodically, and real time. The formula is represented as follows:

Effectiveness = PRI * PQ / APT

4.4.10 Quality Ratio:

It is the most important and easy to understand indicator as it provides a relationship between good item quantity and total number of produced items (PQ). This indicator can be applied at any level of production whether that be a work unit, work center or even the whole plant. Due to its simplicity and accessibility, this indicator is recorded in real time for operator's information. It is represented by the following formula:

Quality ratio = GQ / PQ

4.4.11 Setup Ratio:

This KPI specifies the percentage of the actual processing time expended in setting up the work unit for production. It is the ratio of actual unit setup time (AUST) to actual unit processing time (AUPT). As apparent by the definition, lower the result of this ratio, better it is for the production, as less time will be wasted setting up the machine. It is represented by the following formula:

Setup ratio = AUST / AUPT

4.4.12 Technical efficiency:

This indicator builds a relationship between actual production time (APT) of a work unit and sum of actual production time and unit delay time of a work unit. Actual delay time consists of delays and malfunction caused interruptions. If the company's goal is to achieve 100 percent efficiency in their production, then they should enable their production without any malfunction-caused interruptions.

Technical efficiency = APT / (APT + ADET)

4.4.13 Production Process Ratio:

The production process ratio specifies the relationship between the actual production time (APT) over all work units and work centers involved in a production order and the whole throughput time of a production order which is the actual order execution time (AOET) [38]. AOET is the time including the manufacturing time, delay time and transport time during production. In line with the definition, a low production process ratio suggests that the production order has a lot of idle time or wait time during the production cycle. It is represented by the following formula:

Production process ratio = ΣAPT / AOET

4.4.14 Actual to Planned Scrap:

This indicator is a ratio of actual scrap quantity (SQ) to planned scrap quantity (PSQ) during production. It indicates how much scraped was produced compared with the expected scrap quantity. A low value of this indicator will suggest that scarp is less than expected, which is a good sign for short term goal. But if the indicator is continually showing low values then it means unnecessary material is being allocated by the level 4 system (ERP). The indicator is represented by the following formula:

Actual to planned scrap ratio = SQ / PSQ

4.4.15. First Pass Yield:

The first pass yield designates the percentage of products, which fulfill the quality requirements in the first process run without reworks (good parts)[38]. It is very important to label the products appropriately to identify them as the parts produced during the first production run. It is ratio of goods part to inspected parts:

FPY= GP/IP

4.4.16. Scrap Ratio:

This indicator shows a relationship between scrap quantity and produced quantity of items. It is important for the quality perspective of the production since it involves number of defectives. It is represented by the following formula:

Scrap ratio = SQ / PQ

4.4.17 Rework Ratio:

The ratio of rework quantity (items that need further processing to meet quality standards) to the total produced quantity is known as rework ratio. As this kind of indicator is intrinsically involved in the production process, so data related to can be collected at real time. It is represented by the following formula:

Rework ratio = RQ / PQ

4.4.18 Fall of Ratio:

Before defining this KPI, first there is need to define the fall off quantity. Fall quantity is defined as the difference between the produced quantity (PQ) in the first production order sequence and good quantity on current production order sequence. Hence, the fall off ratio is the ratio of fall quantity and produced quantity in the first operation. This KPI has an influence on the planning quantity (planned scrap) on the production quality per manufacturing step as well as the material wastage[38]. It is represented by the following formula:

Fall off Ratio = (PQ of first production order sequence – GQ of current production order sequence)/ PQ of first production order sequence

4.4.19. Machine Capability Index:

This KPI defines a relationship between dispersion of the process and specification limits. This methods compares the range between the specification limits (USL,LSL) and 6δ dispersion of a series of measurements for a specific characteristic[38]. The machine capability index refers to the ability of the machine to produce specific characteristic of the product with specified quality. This KPI is usually indicated by the customer and its value is typically Cm > 1.67. It is given by the following formula:

$$Cm = (USL - LSL) / (6 * \sigma)$$

4.4.20. Critical Machine Capability Index:

The critical machine capability index (C_{mk}) is the relationship between the dispersion of a process and the upper or lower specification limit (USL, LSL) and its averages (x). The method compares the range between the upper or lower specification limit and its averages and the 3σ dispersion of the series of measurements for a specific characteristic[38]. It can be calculated by the following formula:

$$C_{mku} = (USL - x) / (3 * \sigma) \; ; \; C_{mkl} = (x - LSL) / (3 * \sigma)$$
$$C_{mk} = Min (C_{mku} , C_{mkl})$$

4.4.21. Process Capability Index:

Just like machine capability index, this KPI also specifies the relationship between the dispersion of a process and the specification limits. The process capability index should indicate if the producing process would produce the product according to the specified quality standards[38]. Higher the value of the index, better it is for production. To compute index with accuracy, measurement shall be taken after regular time steps. This KPI is given by the following formula:

$$Cp = (USL - LSL) / (6 * \delta)$$

4.4.22. Critical Process Capability Index:

Just like critical machine capability index, in the context of process measurement, this KPI specifies the relationship between the dispersion of process and the upper or lower specification limit (USL,LSL) and its average of averages[38]. It is given by the following formula:

$$Cpku = (USL - \bar{\bar{X}}) / (3 * \_\square) \; ; \; Cpkl = (\bar{\bar{X}} - LSL) / (3 * \_\square)$$
$$Cpk = Min (Cpku, Cpkl)$$

4.4.21. Comprehensive Energy Consumption:

This KPI is defined as the ratio of total energy consumed in a production cycle to total produced quantity. The motive behind using this KPI is to get energy savings, environmental protection and cost reduction. Moreover, there is no denying the fact that energy consumption is an important factor impacting the costs and bottom line of the company. It is represented by the following formula:

$$e = E/PQ = (\Sigma Mi * Ri + Q) / PQ$$

where:
e: unit energy consumption of an equipment,
E: comprehensive energy consumption,
Mi: actual consumption of certain kind of energy (kilowatt hour)
Ri^a: conversion coefficient of certain kind of energy
Q: algebraic sum of effective energy exchanges with the environment

4.4.22. Inventory Turns:

This metric represents the average number of times inventory stock has been turned over or delivered. It is defined as the ratio of the throughput to average inventory. Higher the inventory turnover, better is the performance of the company in terms of sales. It is shown by the following formula:

Inventory turns = TH / average inventory

4.4.23. Finished Goods Ratio:

It is defined by the ratio of goods quantity produced to consumed material during manufacturing cycle. Higher the ratio, better is the performance of the company. It is represented by the following formula:

Finished goods ratio = GQ / CM

4.4.24. Integrated Goods Ratio:

This KPI is defined as the ratio of produced quantity of integrated goods (IGQ) to the consumed material (CM). Sometimes it happens during manufacturing that some products do not meet the quality standards. These products can be converted into a lower grade of products, let us say Quality B. The combination of these two grades of the products is called as integrated goods. Increase in Quality B group of products will result in decrease in Quality A group of products. The expression for this KPI is given as:

Integrated goods ratio = IGQ / CM

4.4.25. Production Loss Ratio:

This indicator is relevant in the domain of process industry as typically scarp and rework amount are not measured in the process industries[38]. Production Loss element considers the quantity of material lost during storage and transportation. This KPI is demonstrates the relationship between quantity lost and consumed material during production.

Production loss ration = PL / CM

4.4.26. Storage and Transportation Loss Ratio:

This indicator develops the relationship of the quantity lost during storage and transportation to the consumed material during production. It is represented by the following formula:

Storage and transportation loss ratio = STL / CM

4.4.27. Other Loss Ratio:

Other loss ratio refers to the loss in quantity of the material that is not occurred during manufacturing, transportation, and storage. Hence, this KPI is the ratio of other loss (OL) to the consumed material (CM).

Other loss ratio = OL / CM

4.4.28. Equipment load Ratio:

It defines a relationship between total produced quantity (PQ) and equipment production capacity (EPC). Equipment production capacity is the maximum capacity on which the equipment could operate during production. EPC can be either rated or maximum. Production capacity and load rate of equipment are important indicators in a manufacturing enterprise[38]. It is an indicator which shows the efficiency and production state of the equipment. Financially speaking, the value of this indicators affects the cost and bottom line of the enterprise. It is represented by the following formula:

Equipment load ratio = PQ / EPC

4.4.29. Mean Operating Time between Failures:

The mean operating time between failures is calculated as the mean of all time between failures (TBF) for a work unit for all failure instances (FE)[38]. Mean operating time between failure is the measure of expected system reliability evaluated on statical basis from know failure rates of machine and assembly line components. The expression for this KPI is given as follows:

$$MTBF = \sum_{i=1}^{i=FE} \frac{TBF_i}{FE + 1}$$

4.4.30. Mean time to failure:

The mean time to failure (MTTF) is calculated as the mean of all time to failure measures (TTF) for a work unit for all failure instances (FE) [38]. This is an indicator of system reliability calculated with the help of statistical analysis of **mean** times of failures of different parts of the machine or equipment. It is given by the following formula:

$$\mathbf{MTTF = \sum TTF / (FE+1)}$$

4.4.31. Mean Time to Repair:

This KPI is the average time needed to repair a failed component of a machine or work unit. It is calculated as the mean of all time to repair (TTF) work units to all failure events recorded[38]. It is given by the following formula:

$$MTTR = \frac{\sum_{i=1}^{i=FE} TTR_i}{FE + 1}$$

4.4.32. Corrective maintenance ratio:

It is the ratio between corrective maintenance times (CMT) and the sum of corrective and preventive maintenance time (PMT). This indicator is associated with the reliability of the system since it portrays the magnitude of corrective operations within manufacturing activities. A higher value of this ratio wills shows lack of reliability. It is represented by the following formula:

Corrective maintenance ratio = CMT / (CMT + PMT)

4.4.33. Direct energy consumption effectiveness:

Monitoring the energy consumption and planning the energy requirement are of ample importance in the era of sustainable energy. Companies are striving to use green sources of energy and effectively consuming the available energy for their production. For this purpose, this KPI is introduced in ISO 22400 which represents the relationship of planned direct energy consumption effectiveness per item(PDEI) multiplied by the produced quantity (PQ) to the actual direct energy consumption (ADEC)[38]. It is represented by the following formula:

Direct energy consumption effectiveness = PDEI * PQ / ADEC * 100

4.4.34. Direct net energy consumption effectiveness:

This KPI is similar to Direct Energy Consumption Effectiveness but it considers only the produced quantity of an order. Therefore it is defined by the relation of planned direct energy consumption per item (PDEI) multiplied by the food quantity (GQ) to the actual direct energy consumption (ADEC)[38]. It is represented by the following relation:

Direct net energy consumption effectiveness = PDEI * GQ / ADEC * 100

4.4.35 Direct Energy Efficiency:

This indicator provides information about energy consumed by unit of product produced. It is defined as the ratio of actual direct energy consumption (ADEC) to total quantity of products produced (PQ). The unit for this KPI is kWh/unit. It can be represented by the following formula:

Direct energy efficiency = ADEC / PQ

4.4.36. Direct Net Energy Efficiency:

This concept behind this KPI is just like Direct Energy Efficiency, but it considers total number of good products produced (GQ) instead of total number of produced products (PO). It can be represented by the following formula:

Direct net energy efficiency = ADEC / GQ

4.5 KPIs Selection for Custom Manufacturing Industries:

Since our data model and analysis is based on such industries which have the capability to make customer order products and prototypes for their clients, we must choose relevant KPIs that can be implemented in this context.

KPI	Function
1. Worker Efficiency	Production
2. Allocation Ratio	Production
3. Utilization Efficiency	Production
4. Overall Equipment Effectiveness	Production
5. Availability	Production
6. Equipment Load Ratio	Production
7. Technical Efficiency	Production
8. Quality Ratio	Quality
9. Rework Ratio	Quality
10. Actual to Planned Scrap	Quality
11. Mean time to Failure	Maintenance
12. Corrective Maintenance Ratio	Maintenance
13. Inventory Turns	Logistics

Table 24: Proposed KPIs for analysis

First, we neglect all the KPIs that are more suitable for process industries as that is not our scope of work. Next, we must take into consideration the capabilities of custom order industries to appropriately choose KPIs. We list down the following KPIS along with their associated function for our analysis:

4.6 Case Study:

Since the data given in the knowledge-based system is related to an Italian car prototyping company, so now we will compute Key Performance indicators for it. Due to lack of monitoring and unavailability of data, key performance indicators related to production and quality aspects were only calculated. After referring to ISO 22400 and definitions given for elements in it, we mapped an analogy between various elements of ISO 22400 and different fields of tables of knowledge-based system. Consequently, we were able to list down five key performance indicators for the company under study:

1. . Allocation Efficiency
2. Utilization Efficiency
3. Availability
4. Technical Efficiency
5. Quality Ratio
6. Scrap Ratio

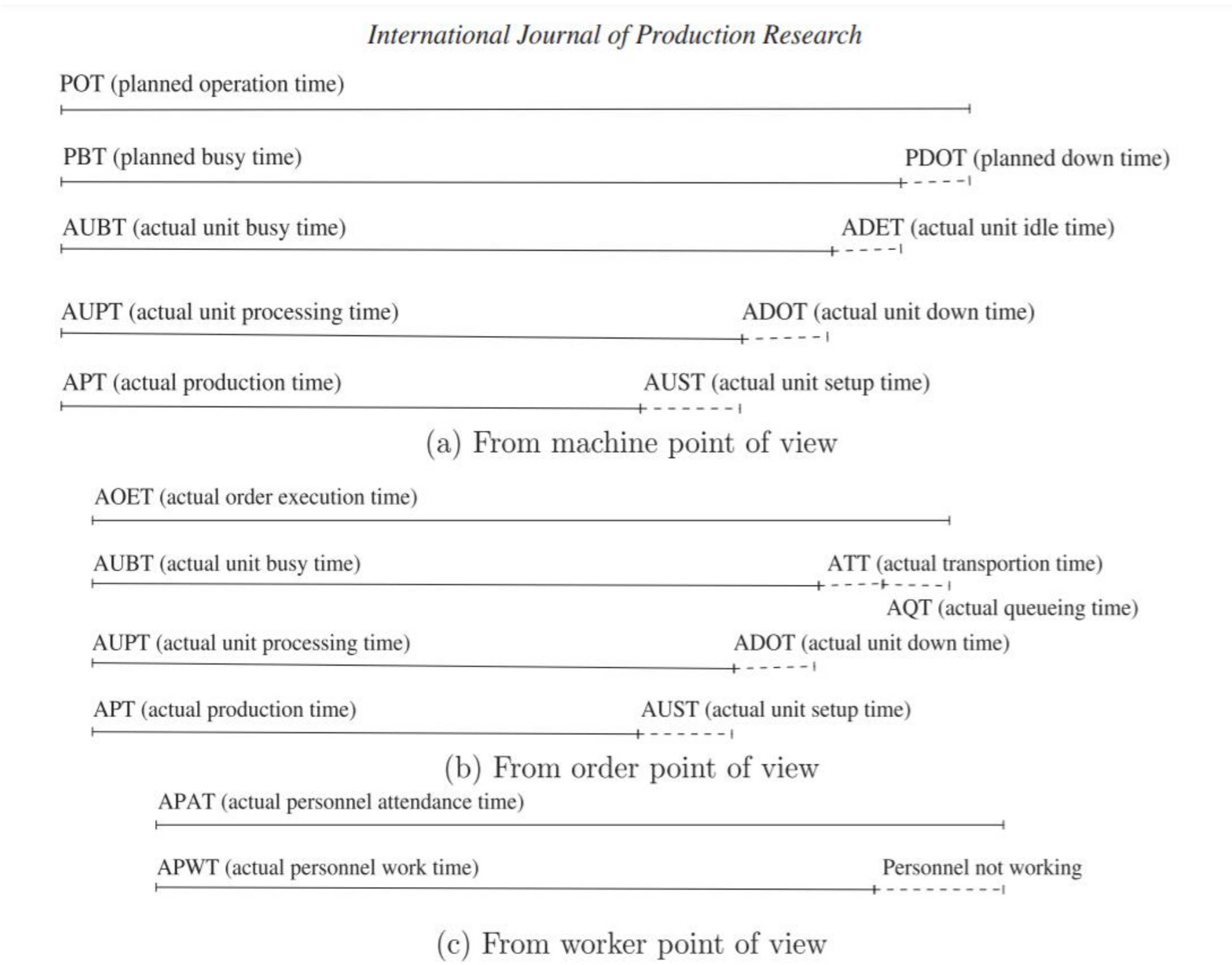

Figure 16: Time elements defined in ISO 22400 [34]

In line with ISO 22400, we can measure time elements from three points of view (see figure 16):

a) From machine point of view
b) From order point of view
c) From worker point of view

Since in our data model, no information about actual queuing time, actual transportation time and personnel working time is given, so we cannot measure time elements from order point of view and worker point of view. Our only focus would be on machine point of view. While analyzing the data of knowledge-based system for KPI computation, two tables are found to be most useful: ProductionDeclarations (see section 3.3.5.1) and Routeheader (see section 3.3.3.2) data. The details about the contents of these tables have already been explained in chapter 3.

4.6.1. ProductionDeclarations Table:

Now we will see the most important tables useful for KPIs computation. In ProductionDeclarations Table **(**Appendix B2), data about the status of the production; **production time, setup time and blocked(down) time**, given in recordtype field is very useful for us. Similarly, for quality perspective, we consider the fields “goodsquantity” and “scrapquanity” as good product quantity and scrapped product quantity. We can now create analogies between our data model and ISO 22400 elements.

We assume:

1. Production time = Actual Production Time (APT)
2. Setup Time = Actual Unit Setup Time
3. Block Time = Actual Down Time

4.6.2. RouteHeader Table:

In RouteHeader table (Appendix B1), duration field corresponds to estimated time of completion of production cycle. We refer to this field of table as Planned Busy Time which is an element defined in the time elements of ISO 22400.

4.6.3 Formulas for KPIs Computation:

The KPIs are computed using the following formulas: (see sections 4.3.2, 4.3.5, 4.3.8, 4.3.10, 4.3.12, 4.3.16 for details).

1. Utilization Efficiency $$= \frac{\text{Actual Production time}(\textit{working})}{\text{Actual Unit busy time } (\textit{setup}+\textit{working}+\textit{down time})}$$

2. Allocation Efficiency $$= \frac{\text{Actual Unit busy time } (\textit{setup}+\textit{working}+\textit{down time})}{\text{Planned Busy Time}}$$

3. Availability $$= \frac{\text{Actual Production Time}(\textit{working time})}{\text{Planned Busy Time}}$$

4. Technical Efficiency $$= \frac{\text{Actual Production Time(working time)}}{\text{Actual Production Time}(\textit{working time})+\text{Actual Down Time}}$$

5. Quality Ratio $$= \frac{\text{Goods quantity}}{\text{Total Produced Quantity}}$$

6. Scrap Ratio $$= \frac{\text{Scrapped Quantity}}{\text{Total Produced Quantity}}$$

Important note: As we are dealing with custom manufacturing industry, so here we are considering number of work pieces worked upon as total produce quantity. Since a work piece can be scrapped on unsuccessful operation, so this would be considered as scrapped quantity.

In table 25, the results of our final KPI computation for out KBS are shown. It shows different revisions of production cycle for a single customer order or project. For each project, six KPIs are calculated to evaluate the performance of company's manufacturing system. Only two KPIs show out of range results: Availability and Allocation Efficiency. By definition, the range of these key performance indicators should be between 0 and 100 percent. But in our case, we

Sr No.	Production Cycles of different projects		KPIs					
			1.Allocation Efficiency	2. Utilization efficiency	3.Availability	4. Technical Efficiency	5. Quality Ratio	6.Scrap Ratio:
1	project 6000	Revision 0	529.80%	54.17%	286.98%	81.25%	62.50%	25.00%
		Revision 1	474.52%	75.93%	360.28%	87.23%	62.50%	25.00%
		Revision 2	531.20%	80.95%	430.02%	80.95%	83.33%	14.58%
2	project 4721	Revision 0	4099.67%	99.80%	4091.33%	100.00%	66.67%	33.33%
		Revision 1	55.83%	99.40%	55.50%	99.70%	100.00%	0.00%
		Revision 2	240.20%	99.92%	240.00%	100.00%	75.00%	25.00%
3	project 4888	Revision 0	PBT duration not given	99.95%	PBT duration not given	100.00%	80.77%	19.23%
4	project 4889	Revision 0	PBT duration not given	78.30%	PBT duration not given	100.00%	90.63%	9.38%
		Revision 1	PBT duration not given	72.30%	PBT duration not given	100.00%	95.12%	4.88%
5	Project 4891 test	Revision 0	PBT duration not given	98.77%	PBT duration not given	99.99%	100.00%	0.00%

Table 25: Final Computation of KPIs

found values beyond 100 percent. Both KPIs have planned busy time in their denominator. As we refer duration of RouteHeader Table as Planned Busy Time, so there is a problem in the estimated duration of the projects.

When we dived deep into the problem, we found out that estimated dutations planned in RouteHeader Table are far less than the actual durations of the projects encountered during production. For instance, planned busy time (duration field in routeheader table) for Project 6000 given in production planning is 4.53 hours according to the estimate of production planners (shown in table 26) but actual unit busy time was 24 hours. Due to substantial difference between durations, we got inconsistent results.

By looking at the results of the key performance indicators, significant insights can be drawn about the efficiency and performance of the company in terms of its manufacturing. For instance, utilization efficiency is a metric of productivity of work unit. By looking at the results of utilization efficiency we can draw two important insights:

id	description	product	revision	duration(hrs)	update_time
4721.K00	Cofano	4721.PZA.PNCOAN2	0	3	1/28/2020 14:52
4721.K01	Cofano	4721.PZA.PNCOAN2	1	6	1/17/2020 14:35
4721.K03	cofano	4721.PZA.PNCOAN2	3	10	3/4/2020 14:40
4721.testAEC.K00	Cofano	4721.testAEC.PZA.PNCOAN2	0	10	3/3/2020
4884.K00	FIANCATA	CR4 GI50/50-E 4100x1950x0.	0		8/8/2020 11:19
4888.K00	FRONTKLAPPE INNENBLECH	4888.PZA.ESSTAN1	0		9/24/2020 9:19
4889.K00	NULL	4889.PZA.ESAN1	0		9/3/2020 13:16
4889.K01	NULL	4889.9451322.E1A.PZA.ESAN	1		11/30/2020 9:08
4891testAEC.K00	VERSTÃ„RKUNG FRONTKLAPPE MITTE HIN	4891testAEC.PZA.NSSCAN1	0		9/17/2020 14:02
4892.K00	NULL	4892.9451323.D1A.PZS.NSAN	0		12/4/2020 15:12
4953.K00	ROOF	4953.PZA.PNTETE2	0	0	7/12/2020 7:57
5014DX.K00	RIVESTIMENTO EST FIANCATA SUP. DX	5014DX.PZD.PNFILA2	0		7/15/2020 11:01
5014SX.K00	RIVESTIMENTO EST FIANCATA SUP. SX	5014SX.PZS.PNFILA2	0		7/15/2020 11:02
6000.K00		6000.PZA.PNTETE3	0	4.53	
6000.K01		6000.PZA.PNTETE3	1	5.69	
6000.K02		6000.PZA.PNTETE3	2	5.93	

Table 26: Duration of Project 6000 in RouteHeader Table (Producion Planning)

- As the company under study is custom manufacturing, therefore there is variation in the values of this KPI since every product is customized according to the needs of the customer.
- Secondly, with the increase in the revision number of production cycle, utilization efficiency increases.

Technical efficiency, which corresponds to minimality of malfunctions during production, of Euro Dies is good. This means that the machines used by Euro Dies are very robust and show little malfunctions during production.

Quality Ratio and Scrap ratio are directly correlated with each other, since the increase of one KPI will lead to decrease in other KPI. By looking at the production data of Euro Dies we can interpret that quality ratio is relatively low, since the nature of custom manufacturing of the company.

5. CONCLUSION AND DISCUSSION

In line with the research question proposed in the first chapter, first we defined the elements needed to evaluate the key performance indicators and then we computed the key performance indicators for an Italian car prototyping company i.e., Euro Dies. Due to lack of availability of some data, many KPIs could not be computed. Due to this reason, evaluation for only six KPIs was carried out. By utilizing the information given in the knowledge-based system (a database obtained by integration of MES and PLM), we made an analogy between the elements defined in ISO 22400[38] and data of knowledge based system obtained with the help of sensors at the shop floor or production unit. Only four KPIs gave a useful result, as the other two KPIs Allocation efficiency and Availability were showing out of range results. This was due to the misinterpretation of one of the elements of the KPIs (Planned Busy Time). Therefore, there is a need for adjustment of this element (duration of route header data). The reason for out-of-range results could be that the management is over optimistic about the duration of the production cycle or they are misinterpreting the meaning of this element.

The benefits of using performance metrics for performance measurement are visible. Before implementing the knowledge-based system, environment of tacit knowledge was prevalent in the company under study. To standardize the information generated during production, data was collected from MES and PLM and integrated into a knowledge based system[36]. The data from this knowledge-based system was utilized to measure the real time performance and efficiency of manufacturing plant. These KPIs can be used to take long or short-term strategic decisions related to company's production.

Due to unavailability of data in KBS, only KPIs related to two categories could be computed: Production and Quality. In the presence of proper measuring systems, KPIs related to other categories can also be computed. For Instance, in the current data model no information regarding the energy consumption, personnel work time, corrective maintenance time, predictive maintenance time, queuing time and transportation time is given. If we incorporate information like actual attendance time and actual work time in our mode, then we can measure worker efficiency. Similarly, machine power ratings and hours of use of machine can be utilized to measure machine power ratings. To add the maintenance KPIs, time taken to carry out corrective and preventive maintenance can be added. Moreover, to measure KPIs from order point of view, product queuing and transportation time can be added.

All these improvements in the data model provide manifold benefits but implementing such monitoring systems at plant level comes with a hefty price. In this regard, while deciding to compute KPIs, an enterprise should align its strategic objectives with its production objectives. Whether an enterprise wants to enhance their capabilities in their product's quality or plant's maintenance, machine energy consumption or speed of production, it totally depends on their strategic objectives.

The purpose of this thesis was to analyze the data framework (KBS) and utilize it to define and compute KPIs for custom manufacturing companies. As custom manufacturing companies have a dynamic and customer centric manufacturing environment, therefore selecting and implementing KPIs in such firms becomes challenging and requires deep analysis and provision of appropriate monitoring systems. Moreover, integration of data from different production systems can be standardized in order to get a more transparent picture of our knowledge-based system. In future work, KPIs related to maintenance, logistics and energy categories can be defined and computed upon the availability of data.

5.1 Delimitations:

There is no denying the fact that COVID-19 has proved fatal for all the businesses and manufacturing companies across the globe. This has proved as a delimitation in my work as I was not able to visit the plant of Italian car prototyping company for in depth understanding of their manufacturing capabilities and HOME project. Moreover, all the data was in Italian language which was a great barrier in my understanding. Also, the project got on hold due to which I was left with limited and raw data for my analysis. I tried my best to make use of the data available and propose useful insights about the behavior of manufacturing of the company under study.

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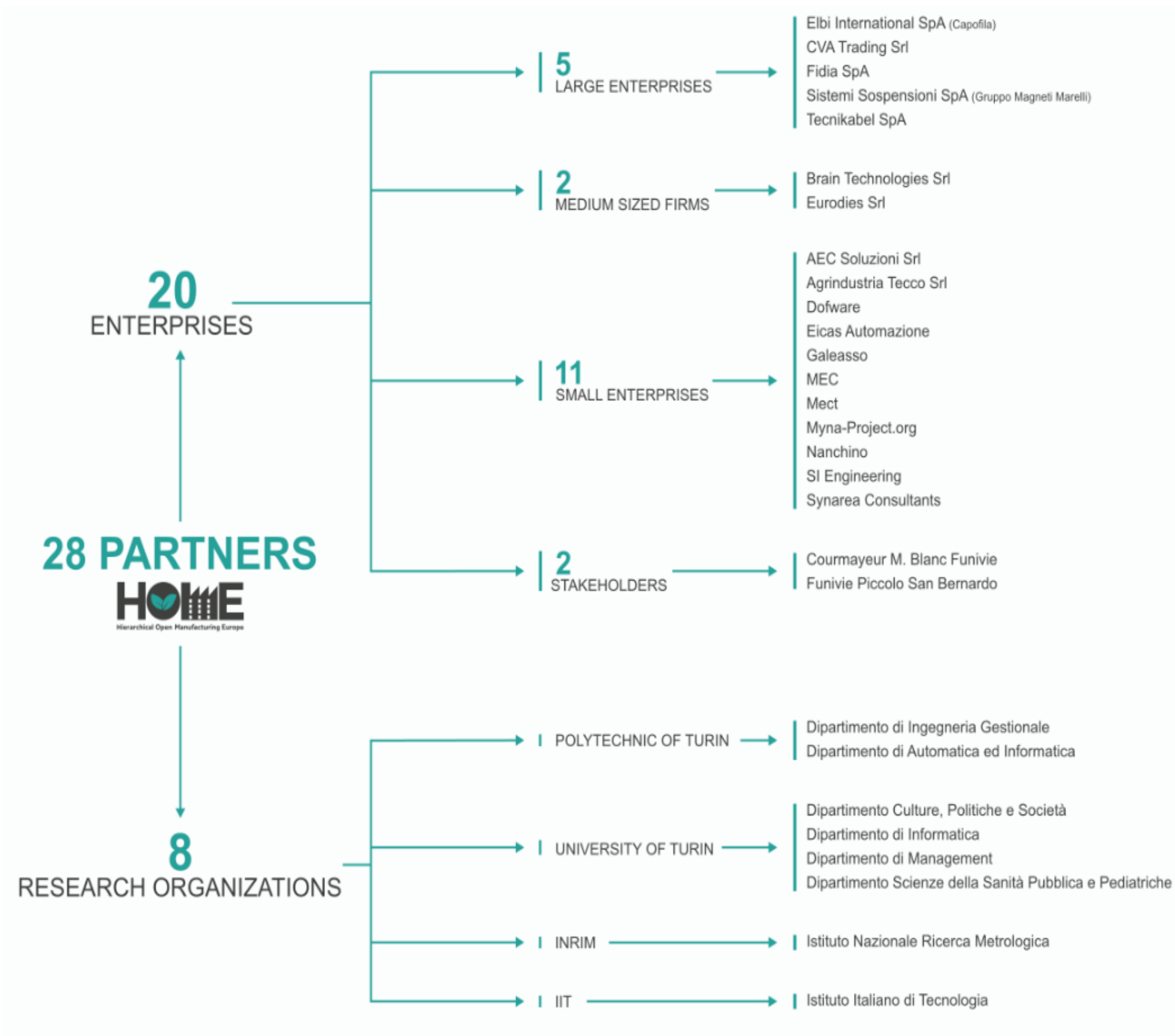
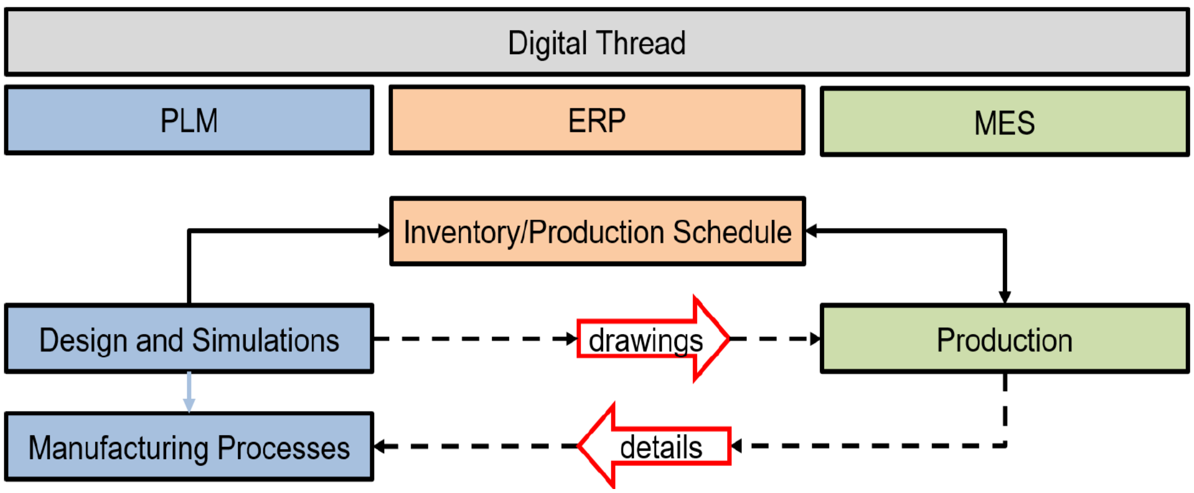
APPENDIX A:

A1: HOME PROJECT PARTNERS



A2: PLM and MES Interaction in Customized Orders [7]



Interaction between PLM and MES

3: Challenges for Enterprise Integration and Interoperability [14]

Challenges	Business	Knowledge	Applications	Communications (ICT)
Grand challenge 1. Collaborative networked organizations (CNOs)[27]	Business and strategy models	Knowledge about business processes and operations in CNOs	Collaborative software solutions	Reliable communication networks
	Reference models of CNOs	Knowledge about core competencies (resources based view)	Software to simulate operation to see parallelism and concurrency	Broadband
	Formalisms for modelling collaboration networks	Sharing principles and operation rules	Tools for monitoring and control of parallelism and concurrency	Wireless applications
Grand challenge 2. Enterprise modelling and reference models [11] [26]	Enterprise measurement systems (e.g. Balanced Score Card)	Description of skills, core competencies, organization roles and knowledge assets	Integration of enterprise applications (ERP, MES, SCADA, factory automation systems)	Open platforms and architectures
	Compensation systems based on enterprise performance measures	On line resources availability and capacity	Workflow management systems (WfMS)	Human computer interaction applications
	Model driven architectures	Balanced automatic vs. manual tasks	Computer supported cooperative work (CSCM)	Friendly user interfaces
Grand challenge 3. Enterprise and processes models interoperability [4] [12]	Integration of business information	Interoperability of models	Standards and interfaces	Standards
	Networked enterprises Ontology mapping and matching Consistent enterprise-wide decision-making structure	Standards (KIF, KQML) Shared Ontology Explicit knowledge models Knowledge management system	Interoperable databases Modular and reconfigurable systems Components based software solutions (plug in/plug out) Simulation software	Interfaces and mediators Interoperability
Grand challenge 4. Validation, verification, qualification and accreditation of enterprise models [22]	Reference models for validation, verification and qualification and accreditation	Ontology and formal modelling	Standards	Interpretability
	New business models evaluation for CNOs	Model-based manufacturing and control	Models formalization Safe systems	Standards
Grand challenge 5. Model reuse and repositories [19] [20]	Distributed business information systems	Ontology and formal modelling	Data mining	Standards
	Unified database enterprise models	Life cycle management information models	Databases and data warehousing Knowledge based Systems	Interfaces Interoperability

APPENDIX B:

B1: RouteHeader Table of KBS for Production Planning

id	description	product	revision	duration(hr	update_time
4721.K00	Cofano	4721.PZA.PNCOAN2	0	3	1/28/2020 14:52
4721.K01	Cofano	4721.PZA.PNCOAN2	1	6	1/17/2020 14:35
4721.K03	cofano	4721.PZA.PNCOAN2	3	10	3/4/2020 14:40
4721.testAEC.K00	Cofano	4721.testAEC.PZA.PNCOAN2	0	10	3/3/2020
4884.K00	FIANCATA	CR4 GI50/50-E 4100x1950x0.75	0		8/8/2020 11:19
4888.K00	FRONTKLAPPE INNENBLECH	4888.PZA.ESSTAN1	0		9/24/2020 9:19
4889.K00	NULL	4889.PZA.ESAN1	0		9/3/2020 13:16
4889.K01	NULL	4889.9451322.E1A.PZA.ESAN1	1		11/30/2020 9:08
4891testAEC.K00	VERSTÃ„RKUNG FRONTKLAPPE MITTE HINTEN	4891testAEC.PZA.NSSCAN1	0		9/17/2020 14:02
4892.K00	NULL	4892.9451323.D1A.PZS.NSAN1	0		12/4/2020 15:12
4953.K00	ROOF	4953.PZA.PNTETE2	0	0	7/12/2020 7:57
5014DX.K00	RIVESTIMENTO EST FIANCATA SUP. DX	5014DX.PZD.PNFILA2	0		7/15/2020 11:01
5014SX.K00	RIVESTIMENTO EST FIANCATA SUP. SX	5014SX.PZS.PNFILA2	0		7/15/2020 11:02
6000.K00		6000.PZA.PNTETE3	0	4.53	
6000.K01		6000.PZA.PNTETE3	1	5.69	
6000.K02		6000.PZA.PNTETE3	2	5.93	

B2: ProductionDeclarations Table of KBS for Production Monitoring (Part 1)

id	machineprogramitem	productionrequestid	productionsegmentsequence	personnelid	machine	goodsquantity	scrapquantity	datefrom	dateto	time	recordtype	reasoncode	annotation	mentcomple	attachment
100001	6000.K00.P.10	6000.01	10	LA1	LA04A3B	8	0	4/3/2019	4/3/2019	3	block	caricamento magazzino			
100002	6000.K00.P.20	6000.01	20	PR3	PR04C2G	7	1	4/3/2019	4/3/2019	3	setup	correzione parametro di pressione			
100003	6000.K00.P.30	6000.01	30	LA7	LA01A4B	6	0	4/4/2019	4/4/2019	5	setup	modifiche al pallet			
100004	6000.K00.P.40	6000.01	40	PR18	PR05C2F	5	1	4/5/2019	4/5/2019	3.5	working				
100005	6000.K00.P.50	6000.01	50	LA12	LA01A4B	5	0	4/5/2019	4/5/2019	2	working	modificato percorso dal pezzo 3			
100006	6000.K00.P.60	6000.01	60	BA5	BAT2	5	0	4/6/2019	4/6/2019	6	working				
100007	6000.K00.P.70	6000.01	70	CO3		5	0	4/7/2019	4/7/2019	1	working				
100008	6000.K00.P.80	6000.01	80	SP2		5	0	4/8/2019	4/8/2019	0.5	working				
100009	6000.K01.P.10	6000.02	10	LA1	LA04A3B	8	0	4/10/2019	4/10/2019	3	working				
100010	6000.K01.P.20	6000.02	20	PR6	PR04C2G	7	1	4/10/2019	4/10/2019	3	working				
100011	6000.K01.P.30	6000.02	30	LA8	LA01A4B	6	0	4/11/2019	4/11/2019	3	setup				
100012	6000.K01.P.40	6000.02	40	PR12	PR05C2F	5	1	4/12/2019	4/12/2019	5	working				
100013	6000.K01.P.50	6000.02	50	LA4	LA01A4B	5	0	4/12/2019	4/12/2019	3.5	setup	modificati parametri laser			
100014	6000.K01.P.60	6000.02	60	PR9	PR05C2F	5	0	4/13/2019	4/13/2019	2	working				
100015	6000.K01.P.70	6000.02	70	BA3	BAT2	5	0	4/14/2019	4/14/2019	6	working				
100016	6000.K01.P.80	6000.02	80	CO2		5	0	4/15/2019	4/15/2019	1	working			1	
100017	6000.K01.P.90	6000.02	90	SP1		5	0	4/16/2019	4/16/2019	0.5	working				
100018	6000.K02.P.10	6000.03	10	LA1	LA04A3B	48	2	4/20/2019	4/20/2019	3	block	scartati 2 pezzi			
100019	6000.K02.P.20	6000.03	20	PR2	PR04C2G	46	3	4/20/2019	4/20/2019	3	block	scartati 3 sviluppi			
100020	6000.K02.P.30	6000.03	30	LA6	LA01A4B	43	0	4/21/2019	4/21/2019	3	working				
100021	6000.K02.P.40	6000.03	40	PR7	PR05C2F	43	0	4/22/2019	4/22/2019	5	working				
100022	6000.K02.P.50	6000.03	50	LA9	LA01A4B	42	1	4/22/2019	4/22/2019	3.5	working				
100023	6000.K02.P.60	6000.03	60	PR13	PR05C2F	41	1	4/23/2019	4/23/2019	2	working				
100024	6000.K02.P.70	6000.03	70	PR4	LA01A4B	40	0	4/24/2019	4/24/2019	6	working			0	
100025	6000.K02.P.80	6000.03	80	BA3	BAT2	40	0	4/25/2019	4/25/2019	1	working				
100026	6000.K02.P.90	6000.03	90	CO1		40	0	4/26/2019	4/26/2019	2	working				
100027	6000.K02.P.100	6000.03	100	SP2		40	0	4/27/2019	4/27/2019	3	working				
100114		20.081BA	1		GLPPRSPNC005	0		2020-09-11 09:54:30+02	2020-09-11 12:00:45+02	2.1	setup			Y	
100115		20.081BA	1		GLPPRSPNC005	315	0	2020-09-11 12:01:11+02	2020-09-11 12:15:56+02	0.25	production			Y	
100088		4721.K00	10	TAGLIO	LA05A3D	1	0	2020-07-16 11:09:14+02	2020-07-16 15:23:22+02	4.24	production			Y	
100086		4721.K01	10	TAGLIO	LA05A3D	0		2020-07-15 11:09:22+02	2020-07-15 11:09:50+02	0.01	setup			Y	
100087		4721.K01	10	TAGLIO	LA05A3D	2	0	2020-07-15 11:10:06+02	2020-07-15 11:10:38+02	0.01	production			Y	
100100		4721.K01	10	TAGLIO	LA05A3D	0		2020-07-17 11:16:06+02	2020-07-17 11:16:20+02	0	setup			Y	
100104		4721.K01	10	TAGLIO	LA05A3D	0		2020-07-17 11:16:32+02	2020-07-17 14:35:54+02	3.32	production			Y	
100105		4721.K01	10	TAGLIO	LA05A3D	0		2020-07-17 14:36:43+02	2020-07-17 14:37:10+02	0.01	block	Attesa map		Y	
110016		4721.K03	10	TAGLIO	LA05A3D	0		2020-03-05 12:25:41+01	2020-03-06 11:51:27+01	23.43	production			Y	
100089		4721.testAEC.K00	10	TAGLIO	LA05A3D	0		2020-07-17 06:36:26+02	2020-07-17 06:36:58+02	0.01	setup			Y	
100129		4888.K00	10	TAGLIO	LA05A3D	0		2020-09-24 09:24:50+02	2020-09-24 10:29:54+02	1.08	setup			Y	
100130		4888.K00	10	TAGLIO	LA05A3D	6	1	2020-09-24 10:30:12+02	2020-09-24 12:26:12+02	1.93	production			Y	
100132		4888.K00	10	TAGLIO	LA05A3D	4	1	2020-09-24 13:34:17+02	2020-09-24 14:19:51+02	0.76	production			Y	
100134		4888.K00	20	TAGLIO	PR01C2L	0		2020-09-24 14:20:49+02	2020-09-24 14:54:25+02	0.56	setup			Y	
100135		4888.K00	30	TAGLIO	LA01A4B	0		2020-09-24 15:05:31+02	2020-09-24 15:07:06+02	0.03	block	Attesa imbutiti		Y	
100204		4888.K00	20	TAGLIO	PR01C2L	9	3	2020-09-24 14:54:38+02	2020-11-27 11:24:06+01	1533.49	production			Y	
100205		4888.K00	30	TAGLIO	LA01A4B	2	0	2020-09-24 15:07:22+02	2020-11-27 11:24:22+01	1533.28	production			Y	
100106		4889.K00	10	TAGLIO	LA05A3D	0		2020-09-03 14:02:58+02	2020-09-03 14:08:04+02	0.09	setup			N	
100107		4889.K00	10	TAGLIO	LA05A3D	14	1	2020-09-03 14:08:16+02	2020-09-03 14:37:22+02	0.49	production			Y	
100108		4889.K00	10	TAGLIO	LA05A3D	6	1	2020-09-03 14:39:26+02	2020-09-03 14:52:08+02	0.21	production				
100109		4889.K00	20	TAGLIO	PR01C2L	0		2020-09-03 14:53:48+02	2020-09-03 15:09:07+02	0.26	setup				
100110		4889.K00	20	TAGLIO	PR01C2L	13	2	2020-09-03 15:09:20+02	2020-09-03 16:18:39+02	1.16	production			Y	
100111		4889.K00	20	TAGLIO	PR01C2L	7	0	2020-09-03 16:29:08+02	2020-09-03 16:55:18+02	0.44	production			Y	
100112		4889.K00	30	TAGLIO	LA01A4B	0		2020-09-03 16:55:52+02	2020-09-03 17:38:47+02	0.72	setup			Y	
100113		4889.K00	30	TAGLIO	LA01A4B	18	2	2020-09-04 07:25:28+02	2020-09-04 08:58:49+02	1.56	production			Y	
100225		4889.K01	10	TAGLIO	LA05A3D	0		2020-12-01 13:57:27+01	2020-12-01 14:01:26+01	0.07	setup			Y	
100226		4889.K01	10	TAGLIO	LA05A3D	3	0	2020-12-01 14:01:41+01	2020-12-01 14:17:28+01	0.26	production			Y	
100227		4889.K01	10	TAGLIO	LA05A3D	5	0	2020-12-02 08:37:25+01	2020-12-02 08:52:42+01	0.25	production				
100229		4889.K01	10	TAGLIO	LA05A3D	12	1	2020-12-02 10:32:53+01	2020-12-02 11:18:34+01	0.76	production			Y	
100234		4889.K01	20	TAGLIO	PR01C2L	0		2020-12-04 10:34:07+01	2020-12-04 11:26:53+01	0.88	setup			Y	
100235		4889.K01	20	TAGLIO	PR01C2L	8	0	2020-12-04 11:27:21+01	2020-12-04 11:54:12+01	0.45	production			Y	
100237		4889.K01	20	TAGLIO	PR01C2L	4	0	2020-12-04 14:25:06+01	2020-12-04 14:35:34+01	0.17	production			Y	
100240		4889.K01	20	TAGLIO	PR01C2L	7	1	2020-12-04 14:40:15+01	2020-12-04 15:15:49+01	0.59	production			Y	
100116		4891testAEC.K00	20	TAGLIO	PR01C2L	0		2020-09-17 17:01:23+02	2020-09-17 17:02:29+02	0.02	block	Rottura stampo		Y	
100117		4891testAEC.K00	10	TAGLIO	LA05A3D	0		2020-09-21 09:37:21+02	2020-09-21 12:27:09+02	2.83	setup			Y	
100127		4891testAEC.K00	20	TAGLIO	PR01C2L	1	0	2020-09-17 17:05:10+02	2020-09-24 09:23:56+02	160.31	production			Y	
100128		4891testAEC.K00	10	TAGLIO	LA05A3D	1	0	2020-09-21 12:27:19+02	2020-09-24 09:24:37+02	68.96	production				

B2: ProductionDeclarations Table of KBS for Production Monitoring (Part 2)

TAGLIO	LA05A3D	0		2020-12-09 12:01:06+01	2020-12-09 12:03:13+01	0.04	setup				
TAGLIO	PR08C2C	0		2020-12-09 12:20:08+01	2020-12-09 16:48:15+01	4.47	setup				
TAGLIO	PR01C2L	0		2020-12-09 17:26:56+01	2020-12-09 17:27:37+01	0.01	block	Attesa sviluppi	fivhrgfhergioherfio	Y	
ED.TAGLIO	ED.LA05A3D	0		2020-02-28 12:39:12+01	2020-02-28 12:54:12+01	0.25	setup				
ED.TAGLIO	ED.LA05A3D	1	0	2020-02-28 12:54:24+01	2020-03-02 16:18:30+01	75.4	production			1	
ED.ASSEMBLAGGIO	ED.LA05A3D	0		2020-03-02 16:22:21+01	2020-03-02 16:35:41+01	0.22	production				
ED.FRESATURA	ED.LA05A3D	2	0	2020-03-02 16:35:55+01	2020-03-03 12:41:56+01	20.1	production				
ED.TAGLIO	ED.LA05A3D	2	3	2020-03-03 12:42:49+01	2020-03-04 11:29:41+01	22.78	production			1	
ED.TAGLIO	ED.LA05A3D	0		2020-03-04 15:06:22+01	2020-03-04 15:07:31+01	0.02	setup				
ED.STAMPAGGIO	ED.PR01C2L	0		2020-03-04 15:25:45+01	2020-03-04 15:25:53+01	0	setup				
ED.TAGLIO	ED.LA05A3D	1	1	2020-03-04 15:08:51+01	2020-03-04 15:32:18+01	0.39	production				
ED.STAMPAGGIO	ED.PR01C2L	2	0	2020-03-04 15:26:05+01	2020-03-04 15:37:06+01	0.18	production				
		0		2020-03-11 12:57:47+01	2020-03-13 16:56:53+01	51.99	setup				
				2020-05-10 18:24:15+02	2020-05-10 18:24:52+02			home	weee - wee 2	1	
	MAC1	28110	0	2019-11-28 15:56:10+01	2020-05-10 18:24:52+02	3937.48	production				
				2020-05-11 16:05:12+02	2020-05-11 16:06:37+02			home			
3				2020-05-14 09:59:39+02	2020-05-14 10:04:29+02						
GINETTA				2020-05-14 11:12:07+02	2020-05-14 11:12:29+02						
1				2020-05-14 11:13:58+02	2020-05-14 11:14:34+02						
1				2020-05-14 15:22:15+02	2020-05-14 15:22:57+02						
1				2020-05-14 15:30:01+02	2020-05-14 15:31:29+02						
1				2020-05-14 16:43:41+02	2020-05-15 15:26:22+02						
1				2020-05-15 15:28:31+02	2020-05-15 15:28:39+02						
1				2020-05-15 15:29:01+02	2020-05-19 10:35:41+02						
luca.siccardi				2020-05-18 10:27:33+02	2020-05-18 10:37:12+02			AEC.003		1	
luca.siccardi				2020-05-18 10:37:32+02	2020-05-21 10:57:25+02			AEC.004			
antonio.tripodi				2020-05-18 10:43:42+02	2020-05-18 10:44:40+02			AEC.001			
antonio.tripodi				2020-05-18 10:45:02+02	2020-06-30 11:08:07+02			AEC.011		1	
				2020-05-19 12:01:34+02	2020-05-19 12:01:45+02			home		1	
enrico.balsamo				2020-05-19 12:53:19+02	2020-05-19 12:53:41+02			AEC.007			
enrico.balsamo				2020-05-19 15:18:53+02	2020-05-19 15:19:09+02			AEC.007			
enrico.balsamo				2020-05-19 16:18:38+02	2020-05-20 15:01:26+02			AEC.007			
enrico.balsamo				2020-05-20 16:16:44+02	2020-05-20 16:23:31+02			AEC.007		1	
enrico.balsamo				2020-05-20 16:23:48+02	2020-05-21 10:59:40+02			AEC.007			
davide.cecconi					2020-05-27 17:52:10+02						
luca.siccardi				2020-05-21 10:57:45+02	2020-05-21 10:59:32+02			AEC.004			
davide.cecconi				2020-05-21 10:57:49+02				AEC.003		1	
luca.siccardi				2020-05-21 10:59:53+02				AEC.004			
enrico.balsamo				2020-05-21 10:59:56+02	2020-05-21 17:28:15+02			AEC.007			
luca.siccardi				2020-05-25 11:07:14+02	2020-05-25 11:43:49+02			AEC.003			
enrico.balsamo				2020-05-25 11:08:29+02	2020-05-25 17:51:12+02			AEC.007			
luca.siccardi				2020-05-25 11:44:01+02	2020-05-25 13:43:38+02			AEC.005			
luca.siccardi				2020-05-25 16:21:27+02	2020-05-25 17:25:29+02			AEC.003			
luca.siccardi				2020-05-25 17:25:40+02	2020-05-26 11:35:24+02			AEC.003			
enrico.balsamo				2020-05-25 17:51:19+02				AEC.005			
luca.siccardi				2020-05-26 11:36:06+02	2020-05-26 11:50:32+02			AEC.004			
luca.siccardi				2020-05-26 11:52:19+02	2020-05-26 12:01:50+02			AEC.005			
luca.siccardi				2020-05-26 12:04:37+02	2020-05-26 17:59:28+02			AEC.004			
1				2020-05-27 12:17:21+02	2020-05-27 12:17:53+02						
1				2020-05-27 12:19:30+02	2020-05-27 12:25:11+02						
BIANCA				2020-05-27 14:45:28+02	2020-05-27 14:45:43+02						
1				2020-05-27 14:51:52+02	2020-05-27 14:53:27+02						
1				2020-05-27 14:53:39+02	2020-05-28 08:58:16+02						
BIANCA				2020-05-27 14:54:06+02							
luca.siccardi				2020-05-27 15:18:25+02				AEC.003			
davide.cecconi				2020-05-27 17:51:51+02							
luca.siccardi				2020-05-28 10:21:21+02	2020-05-28 10:21:30+02			AEC.003			
luca.siccardi				2020-05-29 18:32:11+02	2020-06-17 10:57:22+02			AEC.006			
enrico.balsamo				2020-06-05 12:18:19+02				AEC.010			
davide.cecconi				2020-06-06 16:46:23+02				AEC.005			
luca.siccardi				2020-06-17 14:42:34+02				AEC.004			
enrico.balsamo				2020-06-19 16:13:44+02	2020-06-30 15:43:09+02			AEC.009			
aecsoluzioni				2020-06-25 15:13:17+02	2020-06-25 15:13:38+02			AEC.008			
AEC.marco.montarolo				2020-06-26 12:48:37+02	2020-06-26 12:49:52+02			1000000			
luca.siccardi				2020-06-26 15:03:19+02				AEC.004			
AEC.marco.montarolo				2020-06-29 15:59:04+02				AEC.007			
antonio.tripodi				2020-06-30 11:08:45+02				AEC.011			

B3: ProjectInformation Table of KBS of Product Data

id	customer	description	quantity	duration	customerrequestdate	referencetime	material	:omerreque	naldocum	earlieststarttime	reasontype
4340	VW	BODEN MITTE HINTEN	19	NULL	2020-05-29 00:00:00+02	NULL	CR380LA-GI40/40-U	NULL	NULL	2020-05-29 00:00:00+02	NULL
4721	Frontklappe	Cofano	NULL	NULL	2019-06-05 00:00:00+02	NULL	TL094B	NULL	NULL	2019-06-05 00:00:00+02	NULL
4721.testAEC	Frontklappe	Cofano	35	NULL	2020-05-29 00:00:00+02	NULL	NULL	NULL	NULL	2020-05-29 00:00:00+02	NULL
4828	BMW	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
4884	BMW	NULL	110	6.00	2020-08-07 00:00:00+02	NULL	CR4 GI50/50-E	NULL	NULL	2020-08-07 00:00:00+02	NULL
4888	BMW	FRONTKLAPPE INNENBLECH	NULL	360.00	2020-09-24 00:00:00+02	NULL	AL-5-STD NP-UM	NULL	NULL	2020-09-24 00:00:00+02	NULL
4889	BMW	VERSTÃ„RKUNG FRONTKLAPPE VORN	NULL	12.00	2019-12-02 00:00:00+01	NULL	AL-5-STD NP-UM	NULL	NULL	2019-12-02 00:00:00+01	NULL
4890	BMW	VERSTÃ„RKUNG FRONTKLAPPE HINTEN	NULL	12.00	2019-12-02 00:00:00+01	NULL	AL-5-STD NP-UM	NULL	NULL	2019-12-02 00:00:00+01	NULL
4891testAEC	BMW	VERSTÃ„RKUNG FRONTKLAPPE MITTE HINTEN	NULL	12.00	2020-09-17 00:00:00+02	NULL	AL-5-STD NP-UM	NULL	NULL	2020-09-17 00:00:00+02	NULL
4892	BMW	VERSTÃ„RKUNG SCHARNIER	NULL	NULL	2020-12-04 00:00:00+01	NULL	AL-5-STD NP-UM	NULL	NULL	2020-12-04 00:00:00+01	NULL
4907	BMW	NULL	390	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
4908	BMW	NULL	195	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
4916	DAIMLER	NULL	250	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
4918	DAIMLER	NULL	500	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
4928	FCA	NULL	20	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
4932	DAIMLER	NULL	20	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
4942	DAIMLER	NULL	40	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
4947	PORSCHE	NULL	500	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
4949	PORSCHE	NULL	250	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
4953	EDAG	NULL	15	NULL	2020-06-26 00:00:00+02	NULL	DX56+Z100	NULL	NULL	2020-06-26 00:00:00+02	NULL
4999	FCA	NULL	150	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
5003	FCA	KIT BARRE ANTIINTRUSIONE BAGAGLI CPL	NULL	NULL	2020-06-15 00:00:00+02	NULL	E320+CR2S3	NULL	NULL	2020-06-15 00:00:00+02	NULL
5004	FCA	TUBO SUPERIORE	NULL	NULL	2020-06-22 00:00:00+02	NULL	E320+CR2S3	NULL	NULL	2020-06-22 00:00:00+02	NULL
5005	FCA	TUBO INFERIORE	NULL	NULL	2020-06-22 00:00:00+02	NULL	E320+CR2S3	NULL	NULL	2020-06-22 00:00:00+02	NULL
5007	FCA	STRUTTURA ROLLBAR	NULL	NULL	2020-06-15 00:00:00+02	NULL	E320+CR2S3	NULL	NULL	2020-06-15 00:00:00+02	NULL
5008	FCA	ARCO PRINCIPALE	NULL	NULL	2020-06-22 00:00:00+02	NULL	E320+CR2S3	NULL	NULL	2020-06-22 00:00:00+02	NULL
5009	FCA	TRAVERSA	NULL	NULL	2020-06-22 00:00:00+02	NULL	E320+CR2S3	NULL	NULL	2020-06-22 00:00:00+02	NULL
5010	FCA	CONTRAFFORTE	NULL	NULL	2020-06-22 00:00:00+02	NULL	E320+CR2S3	NULL	NULL	2020-06-22 00:00:00+02	NULL
5011	FCA	SAETTA	NULL	NULL	2020-06-22 00:00:00+02	NULL	E320+CR2S3	NULL	NULL	2020-06-22 00:00:00+02	NULL
5012	FCA	PIASTRINA INFERIORE	NULL	NULL	2020-06-22 00:00:00+02	NULL	LAH340Y410T	NULL	NULL	2020-06-22 00:00:00+02	NULL
5013	FCA	PIASTRINA SUPERIORE	NULL	NULL	2020-06-22 00:00:00+02	NULL	LAH340Y410T	NULL	NULL	2020-06-22 00:00:00+02	NULL
5014	LITLA	RIVESTIMENTO EST FIANCATA SUP. SX	10	NULL	2020-08-28 00:00:00+02	NULL	NULL	NULL	NULL	NULL	NULL
5014DX	LITLA	RIVESTIMENTO EST FIANCATA SUP. DX	10	NULL	2020-08-28 00:00:00+02	NULL	EN-AW6008	NULL	NULL	2020-08-28 00:00:00+02	NULL
5014SX	LITLA	RIVESTIMENTO EST FIANCATA SUP. SX	10	NULL	2020-08-28 00:00:00+02	NULL	EN-AW6008	NULL	NULL	2020-08-28 00:00:00+02	NULL
5019-DX	LITLA	SCATOLAMENTO MONTANTE B SUPERIORE DX	10	NULL	2020-08-28 00:00:00+02	NULL	AA6111	NULL	NULL	2020-08-28 00:00:00+02	NULL
5019-SX	LITLA	SCATOLAMENTO MONTANTE B SUPERIORE SX	10	NULL	2020-07-28 00:00:00+02	NULL	AA6111	NULL	NULL	2020-07-28 00:00:00+02	NULL
5091	PORSCHE	NULL	38	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
5093	AUDI	NULL	100	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
5095	AUDI	NULL	200	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
5123	FCA	NULL	33	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
5132	BMW	NULL	840	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
5133	BMW	NULL	200	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
5134	BMW	NULL	180	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
5140	AUDI	NULL	150	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
5141	AUDI	NULL	410	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
5143	AUDI	NULL	460	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
5145	AUDI	NULL	230	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL
6000	Cliente1	TETTO	NULL	400.00	2019-06-05 00:00:00+02	NULL	0T-DP+GI50/50 3300	NULL	NULL	2019-06-05 00:00:00+02	NULL