Standardization and modularization of Handling system

Optimization of choice of roller conveyors and loading / unloading tables for beam handling
This exam work has been carried out at the School of Engineering in Jönköping in the subject area of product development and production optimization. The work is a part of the Master of Science programme Product Development and Materials Engineering.

The authors take full responsibility for opinions, conclusions and findings presented.

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Scope: 30 credits

Date: 12th June 2019
Throughout this research project I have received a great deal of support and assistance. I would first like to thank my supervisor from Jönköping University, Professor Morteza Poorkiany, whose invaluable suggestions and expertise guided me in the formulation and explanation of the projects and its findings. I would like to acknowledge my colleagues from Ficep, who supported me greatly and were always willing to help me, for their wonderful collaboration. I would particularly like to single out my supervisors Eng. S. Fongaro for the excellent cooperation and for all of the opportunities I was given to conduct my research and further my presentation at Ficep. I would also like to thank my tutors, Dott, A. Bossi and M. Falcetti, for their valuable guidance, providing me with the tools that I needed to choose the right direction and successfully complete my project.
Abstract

This project was commissioned by Ficep S.p.a. and performed in the field of product development with the aim of developing a method for the revision of product architectures in standardized modular configurations.

The handling system for profiled beams has a generally well-established structure and technology among all main competitors in the mechanical carpentry sector, for this reason the key to success in the market is the optimization of the components to minimize redundancies and the ability to promptly satisfy the variegated customers’ demands while still keeping competitive prices.

The major problem in the layout of these systems is the absence of standard rules or mathematical models, relaying mostly on the empirical norms derived from the experience of the designer, thus generating confusion and variants’ proliferation.

For this reason, a standardized and optimized model for generating appropriate configurations according to functional specifics is the final goal of this work.

To hit this target the development process has been analysed and reviewed all the way from the customer offer request to final layout definition, passing through the definition of the technical specifics, architecture of the handling system and inner structure of its components.

The final result is a configurator that, taking the technical specifications of the client as input data, dynamically calculates the structure of the handling system adjusting even the composition of the elements it is made up of and their position for the layout.

As a side project the configurator was used to create a model for cost estimation of the handling system in stages prior to the CAD design of its layout.
Summary

In plants for structural steel machining, the handling system has the function of moving the profiled beams throughout the whole machining cycle. The beams enter the plants unrefined and are loaded and fed to the manufacturing machines by the handling system. The latter has also the function of moving the unfinished product between one working station and the following until the pieces have undergone all the machining to meet the customer specifications. Once again, the handling system takes care of transporting the finished beams to unloading areas to be stocked or dispatched.

Being the part of the implant that varies the most for each customer order this work was commissioned to reorganize the development process of the system with the goal of making it modular and standardize its parts and rules for configuration, generating a method equally applicable for the same process on completely different product families.

The method used to reach the goal had an inductive approach, starting from the collection of information on the market sector of the company and its competitors and data on the customer requests to be satisfied. This background information has then been analysed to formulate a method to go through all the development process of the system from the customer request to the choice and layout of the elements composing the handling system. The requests have been translated in technical specifications of the system by the historical analysis of the handling systems developed from the company for past orders and the guidance of experienced employees from both Ficep and Trennitalia. The construction of a product architecture by means of functional decomposition of the product and mapping of functions to subassemblies made it possible to recognize modules and to define a new modular product structure with standard interfaces between modules. After the definition of standard rules of configuration for the inner structure of the elements of the handling systems as well as for their assembly layout an Excel configurator has been coded to automatize the process.

The configurator is the product of the integration of all the complementary intermediate results previously mentioned and the automation potential offered by the software, which already includes built-in tools for optimization and programming.

As a corollary project, from the association of the configurator to the price lists of all the components of the elements of the handling system, a model for the estimation of prices has been drawn out, creating a linear function of the cost as the algebraic sum of the linearized cost functions of the components.
Keywords and Definitions

*Handling system:* system of automatisms that take care of feeding one or multiple machines or of transferring the semi-finished products among the various machining centres in the plant production line.

*Rollerways:* elements of the handling system that convey the material along the processing line.

*Loading / Unloading Tables:* elements of the handling system that handle the material transversally with respect to the processing line.

*Variety:* the range of products offered by a supplier, intended as variants of the same concept with differences to better fulfil secondary functions.

*Complexity:* characteristic of systems made up of a multiplicity of elements interconnected by a high number of non-simple relationships.

*Mass Customization:* production and distribution of customized goods and services on a mass scale.

*Modularity:* attribute of product architectures in which discrete and mutually independent units embody a specific product function.

*Standardization:* approach that relies on the usage of common fixed components, products, or processes to satisfy heterogeneous needs.

*Configurator:* tool for the calculation of the possible configuration solutions to the user’s requests, often supported by prices relative to each proposal.
4.2 TRANSLATION OF CUSTOMER REQUESTS IN TECHNICAL SPECIFICATIONS OF THE SYSTEM . 45
4.3 EFFECTS OF THE TECHNICAL SPECIFICATIONS ON THE STRUCTURE OF THE HANDLING SYSTEM 45
4.4 PRODUCT ARCHITECTURE ......................................................................................... 48
4.5 RULES FOR CONFIGURATION OF THE HANDLING SYSTEM AND ITS COMPONENTS .......... 50
4.6 CONFIGURATOR ...................................................................................................... 54
4.7 COST ESTIMATION .................................................................................................... 57

5 Discussion and conclusions ............................................................................. 58
5.1 DISCUSSION OF METHOD ..................................................................................... 58
      5.1.1 Literature research ............................................................................................. 58
      5.1.2 Market analysis .................................................................................................. 58
      5.1.3 Brainstorming ................................................................................................... 58
      5.1.4 Case studies ...................................................................................................... 58
      5.1.5 Interviews ......................................................................................................... 58
      5.1.6 Functional decomposition ................................................................................ 58
      5.1.7 Function means tree analysis .......................................................................... 59
      5.1.8 Interface analysis ............................................................................................. 59
      5.1.9 Linear optimization .......................................................................................... 59
      5.2 DISCUSSION OF FINDINGS ................................................................................. 59
      5.2.1 Evaluation of results ......................................................................................... 60
      5.2.2 Research questions and answers ...................................................................... 61
      5.3 CONCLUSIONS .................................................................................................... 63
      5.3.1 Possible future developments ........................................................................... 63

6 References ........................................................................................................... 64
Table of figures

Figure 1 - Air view of Ficep’s Headquarters (Ficep S.p.A., 2018) ........................................... 9
Figure 2 - Milestones in Ficep’s History (Ficep S.p.A., 2019) .................................................. 10
Figure 3 - Example of complete plant layout (courtesy of Ficep S.p.A.) .............................. 11
Figure 4 - Example of powered roller conveyor unit (Trennitalia s.r.l., 2019) ............... 12
Figure 5 - Example of liftable roller conveyor (Trennitalia s.r.l., 2019) .............................. 12
Figure 6 - Example of loading / unloading table with catches structure (Trennitalia s.r.l., 2019) ......................................................................................................................... 13
Figure 7 - Detail view of a catch mechanism (Trennitalia s.r.l., 2019) ................................. 13
Figure 8 - Example of loading / unloading table with carts structure (Trennitalia s.r.l., 2019) ......................................................................................................................... 14
Figure 9 - Detail view of a cart mechanism structure (Trennitalia s.r.l., 2019) ................. 14
Figure 10 - Detail view of combined cart with catch (courtesy of Trennitalia s.r.l.) ... 15
Figure 11 - Example of loading / unloading tables with combined carts with catches (courtesy of Trennitalia s.r.l.) ......................................................................................... 15
Figure 12 - Visualization of the drivers for complexity of a system (Marti, 2007) from (Patzak, 1982) ......................................................................................................................... 18
Figure 13 - Example of elements, relationships, and system structures as a measure of complexity (Marti, 2007) from (Flood & Carson, 1993) ................................................. 19
Figure 14 - Graphical representation of trade-off between costs and benefit associated with product variety (Marti, 2007) from (Rathnow, 1993) .................................................. 19
Figure 15 - Mass produced monogrammed shirt wherewith Davis (1987) introduced the term Mass Customization ...................................................................................................... 20
Figure 16 - Different types of building block systems (mainly according to size) (Miller & Elgård, 1998) after (Borowski, 1961) ................................................................. 22
Figure 17 - Function types and module types in modular and mixed product system (Miller & Elgård, 1998) after (Pahl, Beitz, Feldhusen, & Grote, 1996) ........................................ 22
Figure 18 - Scheme of method for structuring the product architecture (EY, 2015) ... 23
Figure 19 - Difference between de-coupled interface and coupled interface (Ulrich, 1992) ................................................................................................................................. 24
Figure 20 - Different perception of the same object during its lifecycle (Miller & Elgård, 1998) ................................................................................................................................. 24
Figure 21 - Types of modularity (Ulrich & Tung, Fundamentals of Product Modularity, 1991) ........................................................................................................................................... 25
Figure 22 - Different levels of standardization (Agard & Kusiak, 2004).............. 26

Figure 24 - Dominant flow heuristic applied to a generic function structure (Stone, Wood, & Crawford, 1998) ........................................................................................................ 29

Figure 25 - Flow branching heuristic applied to a generic function structure (Stone, Wood, & Crawford, 1998) ........................................................................................................ 29

Figure 26 - Conversion-transmission applied to a generic set of sub-functions .... 30

Figure 27 – Example of the confusion in the choice between modules identified with the 3 heuristic approaches in the example of a SKIL Twist power screwdriver, adapted from (Stone, Wood, & Crawford, 1998) .......................................................... 30

Figure 28 - Example of binary DSM (a) and its equivalent in digraph form (b) (Eppinger & Browning, 2012) ........................................................................................................ 31

Figure 29 - Composite DSM including spatial, energy, information, and material interactions (left) compared to its clustered form (right) (Eppinger & Browning, 2012) ........................................................................................................ 32

Figure 30 - Research design outline ..................................................................... 33

Figure 31 - Examples of Ficep customers’ applications (courtesy of Ficep) ........ 35

Figure 32 - Brainstorming session set (courtesy of Ficep S.p.a.) ......................... 37

Figure 33 - Principle structure of function-means tree showing alternative solutions and a candidate solution (Robotham, 2002) (Hubka & Eder, 1988) ......................... 40

Figure 34 - Knapsack problem depiction (Terh, 2019) ....................................... 41

Figure 35 - Brainstorming session results (courtesy of Ficep S.p.A.) ................. 44

Figure 36 - First configurator interface (section) .................................................. 46

Figure 37 - Loading / unloading tables product architecture .............................. 48

Figure 38 - Roller conveyors product architecture ............................................. 49

Figure 39 - Examples of changes in handling system’s configurations to varying of the working machines (courtesy of Ficep S.p.A.) ................................................................. 50

Figure 40 - Different types of liftable roller conveyors depending on the size of the saw in the plant (courtesy of Ficep S.p.A.) ................................................................. 51

Figure 41 – Differences in the configuration of the handling system when short pieces have to be moved (top) compared to normal length pieces (bottom) (courtesy of Ficep S.p.A.) ........................................................................................................ 52

Figure 45 - Configurator user interface ............................................................. 54

Figure 46 - Setting of the optimization problem parameters behind the configurator’s calculation ........................................................................................................ 55
Figure 47 - Depiction of the base principle behind the choice of rollerways (courtesy of Ficep S.p.A.) ................................................................. 56

Figure 48 - Cost trends for rollerways IN, each line corresponding to a weight class 57

Figure 49 - Area representing the delta cost function between the 1085 kg/m weight class and standard weight (485kg/m) ................................................................. 57

Figure 50 - Example of 3D line layout automatically generated using dummy models of machines ............................................................................... 63

List of tables
Table 1 – Determining cost components in standardization process definition (Perera, Nagarur, & Tabucanon, 2000) ................................................................. 28

Table 2 - Chart relationship representation ................................................................. 31

Table 3 - Effects of the technical specifications on the structure of the handling system .................................................................................. 45

Table 4 - Loading / unloading tables rules for optionals’ configuration chart........... 53

Table 5 - Roller conveyors rules for optionals’ configuration chart ............................ 53

List of equations
Equation (1) ....................................................................................................... 32

Equation (2) ....................................................................................................... 42

Equation (3) ....................................................................................................... 47

Equation (4) ....................................................................................................... 47


1 Introduction

1.1 Background

1.1.1 The company

Ficep S.p.A. is an Italian company producing machinery and complete production systems for the processing of structural steel (beams, profiled beams, thick metal sheets, etc.) and auxiliary machines for the metal forging industry. (Ficep S.p.A., 2018)

It was founded in 1930 by Colombo and Giuliani families as "Fabbrica Italiana Cesio e Punzonatrici" (Italian Shears and Punching Machines Factory), the company has nowadays gained the leading position in the market of automated systems for the manufacturing of structural steel and forging equipment (Ficep S.p.A., 2018) (Ficep S.p.A., 2019).

Ficep’s mainstay lies in the ability of managing the whole manufacturing cycle of structural steel, offering its customers complete and fully automated solutions, specific for each order, a wide range of machine-tools that can work both sheet metals and profiled beams and the supply of turn-key plants.

The headquarters are located in Gazzada Schianno, next to the Alps, where the company has grown up to a surface of over 100,000 square meters. Here their products are followed in all the steps from conception to realization: the implant includes the R&D department complete with laboratories, three areas of machining workshops, one assembly area, the showroom and the main after sales service departments. (Ficep S.p.A., 2018) The same industrial complex houses also the Academy of Technology, whose objective, in line with Ficep’s philosophy, is to share knowledge through training courses and technical workshops. (Ficep S.p.A., 2019)

Figure 1 - Air view of Ficep’s Headquarters (Ficep S.p.A., 2018)
Figure 2 - Milestones in Ficep’s History (Ficep S.p.A., 2019)
1.1.2 The partner

Ficep does not produce the elements of the handling systems in-house but relies on Trennitalia, an external supplier specialized in the development and manufacturing of these components.

As deduced by Cantamessa and Rafele (2002), this trend towards outsourcing manufacturing is driven by the fact that specialized suppliers benefit from lower costs for bulk orders of materials and can develop a higher level of expertise in their field, producing more advanced and better quality products.

Trennitalia has been developing and manufacturing custom-made handling systems to feed sawing machines, drilling machines, sandblasters and painting systems for the processing of steel and sheet metal profiles. The company has been able to keep its products up to date during the years, equipping them with industrial automation to guarantee more efficient and higher volumes machine productivity. (Trennitalia s.r.l., 2019)

The company also takes care of the manufacturing phase of the products, with a workshop in which the staff closely follows them from the assembly phase to the internal final test, making sure that everything corresponds to the personalized goods commissioned. (Trennitalia s.r.l., 2019)

1.1.3 Handling systems

Handling systems perform the functions of feeding one or multiple machines and transferring the semi-finished products among the various machining centres in the plant production line.

In order to always ensure the maximum machine productivity, is then evident the importance of optimizing the material loading / unloading operations as well as the organization of finished products and raw material warehouses. The plants can thus become increasingly complex, based on customer needs, to connect multiple machines of the same type, doubling the production or to link the processing stations with different machines where the semi-finished products must undergo manufacturing. (Trennitalia s.r.l., 2019)

Handling systems are made up of elements belonging to different product families, according to the purposes they must perform and their operating principle. Within each family, a certain product has certain features that can vary to cover the full range of possible technical requests.

Figure 3 - Example of complete plant layout (courtesy of Ficep S.p.A.)
Object of study for this project are two main product families:

- **Rollerways**: conveyance of the material along the processing line.
  In a generic plant, rollerways can be used to convey the material to load or unload machine tools, or auxiliary rollerways that handle the material all along the plant, by feeding specific equipment according to specific demands. Based on customer demands (material’s weight and length, etc...), rollers are positioned at certain distances. Several rollers form a roller conveyor unit and a group of roller conveyors form the rollerway. The rollerways of a plant can be classified as idle or powered rollerways. Generally speaking, the idle rollerways are located near the pincher and their rollers dispose of an adjustable sleeve to enable the pincher to pass.
  The rollerways can be equipped with different accessories according to the various requirements. For example, it is possible that the rollers closer to the working machine can be lifted and/or are applied on a movable device that moves them nearer or farther from the same machine. The rollerways may be equipped with aligning and fixed or roller stop devices to grant material alignment, and safety end-of-stroke devices in the final part of the line to avoid material accidental drops. (Trennitalia s.r.l., 2019)

![Figure 4 - Example of powered roller conveyor unit (Trennitalia s.r.l., 2019)](image)

![Figure 5 - Example of liftable roller conveyor (Trennitalia s.r.l., 2019)](image)
• **Loading / unloading tables:** handle the material transversally to the processing line.

They are used to load or unload the material from the processing line or from auxiliary rollerways.

According to Customer demands (material weight and length, etc...), several transfer devices are combined to a motorization system to form a "table". A control console coordinates all handling operations.

Depending on the way they move the profiled beams, they are divided into three sub-families:

  o **With catches:  QTG**

They handle the material transversally with respect to the processing line, by moving it to the demanded position by means of catches, by dragging it on a low friction surface.

The transversal movement is achieved through a chain, to which a catch is connected. When the chain is moved forward into the working direction, the catch tooth gets in contact with the material and pushes it. When the chain moves in the opposite direction, the catch lowers, passing under the material to be transferred. Once the catch comes out from material underside, it is brought back to working position by a spring.

The quantity of translator arms per table depends on the length of the material to be transported. These machines have also the task of acting as a buffer for the plant, as it is possible to store onto the roller conveyor several semi-finished products which will then be loaded one at a time. (Trennitalia s.r.l., 2019)

![Figure 6 - Example of loading / unloading table with catches structure](image1)

![Figure 7 - Detail view of a catch mechanism](image2)
With carts: QTH

The transversal movement with respect to the processing line is achieved through a chain, to which a cart is connected. Through a hydraulic cylinder powered by a hydraulic unit, the cart lifts the material above the working level and then moves it to the required direction. Once the material has been positioned, the cart lowers below the working level, exits from the working area and positions for following processing operation. (Trennitalia s.r.l., 2019)

Figure 8 - Example of loading / unloading table with carts structure (Trennitalia s.r.l., 2019)

Figure 9 - Detail view of a cart mechanism structure (Trennitalia s.r.l., 2019)
**Combined: QTHG**

On demand, QTH tables can be supplied in the combined version allowing to transfer the beams by dragging as well as by lifting (like normal QTH). In this case, the table is referred to as QTHG and can be configured according to both working modes.

These loading / unloading tables are equipped with the following components: intermediate lifting, block valve and a special cart fitted with a catch applied in the demanded working direction.

![Image of combined cart with catch](image10)

**Figure 10 - Detail view of combined cart with catch (courtesy of Trennitalia s.r.l.)**

The dragging operation mode consists in:

1. position the cart to “position down”
2. lift the cart to an “intermediate” position. This means that the catch, but not the cart, will protrude by approximately 20 mm from the working level;
3. push the beam by means of the catch by activating the cart movement towards the catch.

Beams are dragged along a polyethylene surface.

![Image of loading / unloading tables with combined carts with catches](image11)

**Figure 11 - Example of loading / unloading tables with combined carts with catches (courtesy of Trennitalia s.r.l.)**

**1.1.4 State of the art**

The choice of the elements for each customer request is now preliminarily drafted by Ficep’s R&D personnel to assess the costs for the commercial offer and then transmitted to Trennitalia which engineers the handling system and defines the real layout. This process is time consuming and, relying mostly on the employee experience, it’s often not consistent from time to time and a cause of a mismatch in offer prices vs. costs, resulting in loss of revenue.
1.2 Purpose and research questions

1.2.1 Purpose

In the market sector of beams and structural steel profiles processing machines, Ficep is among the few manufacturers in the world able to supply the complete system (turnkey factory), including machine tools (drilling machines, saws, thermal cutting, etc.) and the automatic handling units, integrated in a completely automated and interconnected system in the factory network.

To consolidate its leading position on the market and offer its customers an even higher-performance product, Ficep has decided to launch a wide-ranging project, called Smart Modular Steel Fabrication System, aimed at the study of a more technologically advanced and versatile version of its catalogue, able to perform a greater variety of machining, designed in a modular configuration, highly automated and integrated with the production management system.

Currently the plants and production systems supplied by Ficep are "unique" systems designed specifically for each application requested by the customer. The objective of the project is to redefine and redesign the entire range of machines in the carpentry segment in a modular configuration.

The morphology of the lines' lay-outs can be very different, depending on the types of machining to be carried out, the end-use destination (e.g. civil buildings, large infrastructures, bridges, etc.) and the customer's production management. It is important to be ready to respond quickly to all customer needs, expanding, modifying and reconfiguring production lines in ever shorter times in order to offer prompt responses in a market increasingly characterized by the reduction in project execution times.

Objective of the project is therefore the standardization of the components, identifying some basic elements (or basic functional units) by whose combination it will be possible to recreate the entire range of existing models of the handling system but with the bonus of added reconfigurability and adaptivity.

The corollary to this process is the connection with the supplier price list, necessary for the development of a more accurate cost estimation model for customer offers.

From a more general point of view the goal of this research is the creation of a method for the redesign of existing product architectures in modular configuration, able to easily and consistently generate variety combining standardized and interchangeable functional units according to fixed rules.

1.2.2 Research questions

How can the handling system composition be optimized by reviewing the design of its components and assembly rules according to functional specifics?

RQ 1 How can customer requests be translated into technical specifications of the system in a standard way?

RQ 2 What are the relationships between technical specifications and physical characteristics of the constitutive elements of the handling system?

RQ 3 How can a new architecture of the products in modular configuration be derived still guaranteeing the fulfilment of each function?

RQ 4 What are the rules for the configuration of the handling system and its components?

RQ 5 What model allows a reasonable estimation of the costs of the system?
1.3 Delimitations

The thesis project is part of a larger plan in the company aimed at developing an innovative technology in the field of structural steel production systems.

The Smart Modular Steel Fabrication System project involves all range of machines produced by Ficep as well as the development of new ones in order to offer a wider variety of machining and a higher degree of automation and integration with factory management systems (in view of Industry 4.0).

The objective is the creation of functional standalone units, complete with electrical system and software ready to be assembled in line with the processing machines, so that, once connected, the plant will be ready to work, and it will not be necessary to realize the entire electrical system in loco, as it is now.

The modularization process will involve both the physical part of the system (mechanical and electrical system) and the software. For each structural module identified from the mechanical point of view, the electrical interconnections will be standardized as well and each unit will also be equipped with its own control unit (PLC), with its own software module ready to interface with the other modules of the system.

The scope of this paper, however, is limited to the mechanical aspect of this process of standardization and modularization and restricted to the basic elements of the handling system: rollerways and loading / unloading tables.

1.4 Outline

This paperwork follows the structure of the research work performed, starting with a brief summary of the theoretical background concerning the concepts of complexity, mass customization, modularity and standardization used to gain knowledge on how to arrange the work in order to answer the research questions.

Following this section, in the method and implementation chapter, after a general outline of which methods have been used get an answer to each research question and the results obtained through them, each method is presented explaining also its implementation in the project.

In findings and analysis, the results obtained in each step are presented in consecutive order, showing how each one is at the same time the result of the previous analysis and the starting point of the following one. The final embodiment of all the theoretical knowledge regarding configuration rules and redesign of the components in modular and standardized subassemblies is explained in the configurator section.

The pros and cons of methods employed as well as the relevance of the results obtained are finally presented in the discussion and conclusion section.
2 Theoretical background

The abrupt exponential acceleration in technological change rate has sparked a social revolution towards “The Temporary Society” as predicted by Bennis and Slater in far (1968) and lead to what the Tofflers described as “Future Shock” (1970) in the homonymous book. Despite both books being 50 years old, the hypothesis for the future inferred from their sociological analysis results pretty close to today’s reality. The accelerative thrust in manufacturing advancement is driven by technology and powered by the diffusion of knowledge; internet guarantees access to information tearing down barriers and cancelling distances in the same way gasoline, once ignited, immediately spreads fire way beyond the soaked area. (Toffler & Toffler, 1970)

In the past, market swings were extremely slow, so the main focus when developing a product was to ensure its durability, following the policy of permanence. Nowadays instead, due to the advance of technology and the faster changing markets, the tendency is towards the “throw-away” economy, where it’s quicker and cheaper to replace with an industrially produced double than to opt for repair work which generally remains a handcraft operation. (Toffler & Toffler, 1970)

The reason behind the need of a new product is not limited to obsolescence or breakage, but it’s more often a consequence of the impermanence of customer needs. (Toffler & Toffler, 1970)
Manufacturing companies are nowadays expected to supply their customer with an increasing variety of products to satisfy their unique needs, hence arises the problem of how to rethink the whole production system in a more agile and flexible configuration. (Piller & Kumar, 2006) (Ristov & Ristova, 2011)

2.1.1 Complexity

Flood and Carson (1993) define a system as “an assembly of elements related in an organized whole”, making immediately clear for the reader that its two distinctive properties are the number of elements that constitute it and the relationships that keep them together. The way in which they are mutually connected to each other describes the structure of the system.

Marti (2007) translating Patzak (1982) individuates in the number and types of both elements and relationships the determining factors causing complexity to arise.

Figure 12 - Visualization of the drivers for complexity of a system (Marti, 2007) from (Patzak, 1982)

"Many relationships"  "Many kinds of relationships"
"Many elements"  "Many kinds of elements"
To better give an idea of how quickly the number of possible variants of a product can grow, it’s enough to think of a three-element system. Keeping the elements constant and assuming the relationships between them as bidirectional and boolean (present=1, absent=0), the system has 8 possible configurations. Doubling the number of elements, from 3 to 6, the number of possible system structures becomes $32 \cdot 768$, more than 4,000 times the result of the first case. (Marti, 2007) from (Flood & Carson, 1993)

Each one of the elements and relationships in turn has specific qualities or properties, referred to as attributes, some of which can be changed to guarantee variety. (Flood & Carson, 1993)

Nowadays a product in order to be competitive in the market must be able to meet customer requirements in terms of specifications that generate the so-called external complexity. To satisfy the requests by adjusting the product’s attributes, developers introduce variety in the design. Variety, however, doesn’t affect just the product structure, but “spreads to all functional areas” of the manufacturing company, causing internal complexity. Of great interest is therefore to find the optimum combination between the creation of product variants and the additional cost associated with them. (Marti, 2007)

Ulrich and Tung (1991) however, point out that variety is only appealing for customers if it enhances the functionality of the product, especially “in terms of the specific performance characteristics of the product relative to a particular functional element”. The indication on which attributes it’s necessary to change in order to meet a specific need can be found in the product architecture. (Ulrich & Tung, 1991)
2.1.2 Mass customization

To resolve the conflict between uniformity and variety, economy of scale and economy of scope, an apparently oxymoronic concept has been introduced: Mass Customization, defined as “production and distribution of customized goods and services on a mass basis” (Davis, 1987). The term mass customization was coined by Stanley Davis in his visionary work appropriately titled Future Perfect (1987) wherewith he subverted the industrial mindset of that time in the same way Einstein’s theories shook classical physics. The author develops this revolutionary concept from the application of science to business, as the former derives fundamental properties of the universe, whose comprehension makes them transferrable to the creation of products and services for the latter. (Davis, 1987) (Pine, 1993)

Possibly inspired by Einstein’s approach, he analyses three of the fundamental quantities of the universe, time, space and matter but from the point of view of industrial economy, with the aim of fundamentally transforming their meaning and the way in which they are perceived, from constraints to resources. (Davis, 1987)

The breakup point with tradition lays in the switch from a producer centred to the new customer centred reference system: Davis (1987) summarizes the key points of this shift as any time, any place, no matter.

Emblematic of this attention towards the customer is the example with which this term was introduced, the customization of mass-produced shirts, challenging at the same time both the dichotomies of either/or and part/whole. Indeed, the fact that every one of the shirts is mass produced with the same specifications makes it a part of a whole batch, but since each one could be individually personalized already in the production line it becomes simultaneously a whole and a part of the whole. (Davis, 1987) (Pine, 1993)

Consequently, the idea of mass market loses its meaning and, as Davis (1987) recognises, every customer is his own market. Pine (2011) goes one step further stating that “every customer is multiple markets” unfolding this concise proposition with the following example:

“Think of travel. If you travel for business, you want one thing from the airline, the hotel, the rental car company, the restaurants you frequent, and so forth. Bring your spouse with you and suddenly all of those requirements change. Bring the kids along and they change again. Travel for pleasure, rather than for business, and each permutation mutates yet again.” (Pine, 2011)
Piller and Kumar (2006) agree with Pine (2011), Victor and Boynton (1993) on the dangers of excessive variety to blindly pursue the maximum customization. “Customer satisfaction may not only plateau after a certain customization level of the product, it may decrease because of the frustration a customer feels due to excessive choice or variety.” (Piller & Kumar, 2006)

Toffler and Toffler (1970) used the term overchoice to identify this phenomenon and by reasoning on the worst possible scenario described a dystopian situation in which people are paralyzed in front of decisions by a surfeit of variety.

To avoid this hyperbolical effect, it is then necessary to develop “some sort of design tool” to help customers bring into focus their generally blurry needs without having to articulate it (Pine, 2011), set the best degree of customization (which is hardly ever the maximum) and define the mass customization specifics (Piller & Kumar, 2006), as “Fundamentally customers don’t want choice; they just want exactly what they want” (Pine, 2011).

2.1.3 Modularity

As emerged from the historical excursus introducing this section, the challenge for companies has nowadays become to offer their clients customizable and flexible products keeping at the same time prices in line with the ones of mass production. This prompts the question as to how to handle the deriving complexity (Schuh, Rudolf, & Vogels, 2014)

Finding the point of optimum balance between external variance and internal standardization is the main motivation behind the choice of a modular approach in the configuration of the product. (EY, 2015)

“If we want to perfectly understand a problem we must reduce it to its simplest terms and divide it up into the smallest possible parts.” (Descartes, 1619-1630)

Several centuries later, Clark and Baldwin (2000) open their book by suggesting the same strategy to manage complexity, introducing the concept of modularity. Extremely peculiar is the fact that their definition of modularity, has itself the same structure as the concept that it must convey. By readapting McClelland and Rumelhart (1986), Clark and Baldwin (2000) define modularity as the combination of two distinct ideas, whose sum is greater than the sum of its parts (Aristotélēs, IV century b.C): the first one being interdependence within and independence across modules, while the other incorporates abstraction, information hiding, and interface.

Designing a modular product then basically means conceive it as made up of discrete and mutually independent units that embody a specific abstract product task (function), this way dividing the complexity of the whole system and hiding it in each component. The standardization of the interfaces guarantees the integrability of the modules in the final structure, combining the functions while maintaining the independence of the structure. (EY, 2015) (Baldwin & Clark, 2000)

The term modulus takes its origin as a diminutive of modus (“measure”) and has initially been used as conventional unit of measurement for the proportioning between the various parts of a whole, were it the human body, ships or buildings. The term was formalised by Vitruvius in the third chapter of the fourth book of his opera De Architectura, reason why the term with this connotation is also referred to as Vitruvian modulus (Miller & Elgård, 1998)

The term remained mainly used in the fields of art and architecture, until Bauhaus, an architecture movement itself, introduced the aspect of interface compatibility to its meaning. The concept of module became closely linked to the idea of “building block”, intended to be a specific room, each of which could be connected to the others in
different arrangements thanks to the standardised interfaces, in an attempt to rationalise geometries, allowing the usage of prefabricated materials to increase the efficiency during both the planning and construction phases. (Miller & Elgård, 1998) This formulation raised the interest of the mechanical world that decided to implement this approach to the design of products and machines to create variety the combination and exchange of different building blocks. (Miller & Elgård, 1998)

Miller & Elgård (1998) attribute to Pahl, Beitz, Feldhusen, and Grote (1996) the integration of functionality in the concept of module and the categorization of the latter on the base of the kind of function they embody, automatically excluding from the definition anything that cannot be assigned to these categories. They distinguish type of function, importance, complexity, combination, resolution, concretization and application. (Miller & Elgård, 1998) citing (Pahl, Beitz, Feldhusen, & Grote, 1996)

Albers, Burkardt, Sauter and Sedchaicharn (2008) define them as:

**Basic functions:** fundamental scopes of the product, not variable in principle.

**Auxiliary functions:** required for the connection of the various product’s components.

**Special functions:** additional sub-functions related to specific product variants.

**Auxiliary functions:** necessary for the adaptation of the product with the others.
Theoretical background

The tool that associates the functional structure to physical components in the product structure is the product architecture. (Ulrich, 1992)

Ulrich (1992) defines more rigorously product architecture as:

1. The arrangement of functional elements
2. The mapping from functional elements to physical components
3. The specification of the interfaces between interacting physical components

In order to derive the functional product structure, it is necessary to clearly state the main function of the product and then proceed top-down individuating the hierarchy of all the subfunctions that make up the product task, each one expressed in an abstract and solution-neutral way. (EY, 2015)

The physical components proposed to fulfil the various functions, are not necessarily a single hardware element, but can as well be subassemblies whose elements address a function altogether or even software subroutines. (Ulrich, 1992)

The degree of modularity is measurable through the morphology of the mapping, i.e. “the level of functional independence of the components and the interface standardization between different elements of the product structure”. (EY, 2015)

Functional independence investigates the complexity of the relationships between functions and components. These relations can essentially be of two kinds:

- “one-to-one”: biunique relation between function and component (Ulrich, 1992)
  (EY, 2015)
- “non one-to-one”: complex mapping in which several functions are implemented by more than one component, and in which several components each implement more than one function (Ulrich, 1992)

Therefore, one product will be all the more modular, the more one-to-one relationships characterise its architecture. (EY, 2015)

The process of modularization indeed “is not a process to turn a non–modular into a completely modular product but it can be applied to increase the degree of modularity”. (Albers, Burkardt, Sauter, & Sedchaicharn, 2008) citing (Rapp, 1999)

---

**Figure 18** - Scheme of method for structuring the product architecture (EY, 2015)
Another fundamental aspect in the analysis of the product architecture is the coupling / decoupling of the interfaces of the components, i.e. the extent the change of one component will affect all the components that interface with it in order to maintain the functionality of the while system unaffected. (Ulrich, 1992)

In the example in the picture, the eventual change of thickness of the bed would only affect the box in the system on the right (coupled interface), while, thanks to the nature of their connection, the one on the left would remain the same (decoupled interface). (Ulrich, 1992)

The constraints on interfaces do not only depend on the geometry though, considering that for the system to correctly perform, energy, information and material have to flow without obstacles on their way. (Ulrich & Tung, 1991) (Miller & Elgård, 1998)

It is important to note that Ulrich and Tung (1991) describe modularity as a “relative property” since it can only be quantified in relation to other products. Furthermore, modularity is a principle that can be applied at several levels of the product as explained by Miller and Elgård (1998) with the recapitulatory scheme below, using the example of a flowmeter:

1. The life cycle of the flowmeter starts at the manufacturing company, where it is seen as a product
2. It is then dispatched to a manufacturer of energy-meter for hot water, where it is used as a module, together with a processor and a temperature gauge.
3. Finally, when the energy meter is installed in a large process plant, the flowmeter becomes a component

To sum up the contents presented in this section so far, functional independence and standardized interfaces guarantee interchangeability of the constituent components consequently allowing to reach variety of products while at the same time reducing variety in manufacturing. (Ulrich & Tung, 1991) (EY, 2015)
Theoretical background

The image below displays the types of modularity presented by Ulrich and Tung (1991)

![Types of modularity](image)

**Component-sharing Modularity**
Common components used in the design of a product. Products are uniquely designed around a base unit of common components.
Example: Elevators

**Component-swapping Modularity**
Ability to switch options on a standard product. Modules are selected from a list of options to be added to a base product.
Example: Personal computers

**Cut-to-Fit Modularity**
Alters the dimensions of a module before combining it with other modules. Used where products have unique dimensions such as length, width, or height.
Example: Eyeglasses

**Mix Modularity**
Also similar to component swapping, but is distinguished by the fact that when combined, the modules lose their unique identity.
Example: House paint

**Bus Modularity**
Ability to add a module to an existing series, when one or more modules are added to an existing base.
Example: Track lighting

**Sectional Modularity**
Similar to component swapping, but focuses on arranging standard modules in a unique pattern.
Example: Legos

Figure 21 - Types of modularity (Ulrich & Tung, Fundamentals of Product Modularity, 1991)

To develop the perfect structure of the products, the R&D can resort to this scheme and even combine two or more of these approaches.

To conclude, using the wording proposed by Miller and Elgård (1998), the main drivers behind modularization result to be:

- **Variety creation (customize)**
  Offer the customer differently tailored products combining standard modules

- **Use of similarities (reuse resources and standardize)**
  Reuse knowledge to speed up work, cut all redundancies, limit risks focusing on improving the stable solutions (modules) by reducing internal variety

- **Complexity Reduction**
  Enhance comprehension of the problem by diving it and resolving its subparts with different groups working in parallel

As a final note, it is essential to evaluate in each case the cost-benefit balance of such approach and to pursue “an optimal rather than maximal degree of modularity”. (EY, 2015)
2.1.4 Standardization

The higher degree of variety reachable for instance through modularization, increases the internal complexity of the product, jeopardizing the performance of the whole production system and causing the costs to rise. (Perera, Nagarur, & Tabucanon, 2000)

One way to reduce the number of variables maintaining the same level of variety is represented by standardization, since, as indicated by Agard and Kusiak (2004), this technique focuses on “the use of common components, products, or processes to satisfy heterogeneous needs”.

This approach is especially suitable in tandem with modularization, as not only does standardization aim to reduce the newly arisen internal complexity, but throughout the process of modularization, the function of each component as well as the interface of the component with the rest of the product has to be clearly defined, giving the instruments for the standardization of components on a functional base. (Ulrich & Tung, 1991)

The more standard the interfaces are, the higher level of interchangeability could be reached, allowing not just to swap different solutions for a specific product function, but even to use the same one or more components on different products. (Ulrich & Tung, 1991)

It has been proved that standardization improves efficiency by means of access to economy of scale and simplification of manufacturing processes. Agard and Kusiak (2004) show that standardization can reach different depths in the development of the product:

- Commonality of components in different products
- Standardization of components for comparable requirements
- Standardization of the manufacturing process (Agard & Kusiak, 2004)

![Figure 22 - Different levels of standardization (Agard & Kusiak, 2004)](image-url)
According to Ulrich and Tung (1991) the advantages of standardization include:
- reduced component costs because of economies of scale in component production,
- enhanced component performance arising from ongoing refinement,
- broad amortization of product development costs,
- reduced materials management costs because of a reduction in part numbers used in the production system.

While the choice of a standardized component could cause the following collateral costs: (Ulrich & Tung, 1991)
- a mismatch between ideal performance characteristics and those available in standard components,
- an increase in unit costs arising from the use of a component with excess (costly) capability.

With this premise, it is evident that the main drivers for standardization are grouping of functions in one component and cost reduction.

Perera, Nagarur and Tabucanon (2000) examine qualitatively the cost to be considered in the evaluation of which components to standardize as summed up with the chart in the next page.

The authors, as a concluding note underline the importance of logistic issues deriving from the supply of the component, suggesting a further evaluation of make or buy decision, manufacturing process and supplier choice in the light of the economic analysis just carried out.
| Inventory Costs | **Cycle inventory cost**  
Being dependent on the order quantity can benefit from standardization of components as “total order quantity for the standardized component is usually less than the sum of the quantities ordered for unique components” |
| **Safety stock cost**  
Can take advantage of component standardization by risk pooling |
| **Purchasing costs** |  
| **Price**  
Due to the general policy of quantity discount, buying a larger batch of one component will be less expensive than several smaller batches of different components |
| **Order cost**  
Despite being generally independent of the order quantity, can still take advantage of standardization since by reducing component variety it is possible to place orders less often |
| **Transportation cost**  
Taking advantage of the same discounts as the price, larger lots sizes due to component standardization guarantee lower costs |
| **Manufacturing cost** |  
| **Production cost**  
Includes material, processing and, if needed, design cost. On one hand, being a standardized component multifunctional, it often results to be more expensive, even though on the other hand it has to be considered that larger batches need less interruptions in the production, thus having a positive effect on the production cost. (Perera, Nagarur, & Tabucanon, 2000) |
| **Setup cost**  
A more uniform production with larger lots needs less setup and changeovers, thereby reducing setup costs |
| **Work-in-process cost**  
The reduction of variety that follows standardization can significantly cut WIP inventories |
| **Design and Reconfiguration Cost** |  
In case standardization generates new components, both manufactured and purchased components will come across costs due to the necessity of new tools/moulds or connected to the readjustment of the existing ones to meet the new design specifications. |
| **Assembly Cost** |  
| **Functional cost**  
Cost of the assembly operations of the component, depending only on the characteristics of the components and not on the number of variants. |
| **Variety cost**  
Result of the costs of the individual characteristics of the variants, includes costs of changeovers and variety of necessary tools |
| **Modification Cost of Related Components** |  
| **One-time design and reconfiguration cost**  
Cost depending on the redesign/reconfiguration of the components that have a relationship with the standardized one to accommodate it |
| **Running cost**  
Encloses the delta costs of material, processing, inventory etc. between pre and post standardization |

Table 1 – Determining cost components in standardization process definition (Perera, Nagarur, & Tabucanon, 2000)
2.1.5 Previous similar studies

**Heuristic method**

The heuristic method takes as starting point the functional decomposition of the product according to the type of flow (material, energy, signal) associated with it, adding the concept of functional dependency to “further arrange functional models with respect to time” (Stone, Wood, & Crawford, 1998). The order in which the functions must be performed can be sequential or parallel according to the same logic as for electricity flows. When one flow passes through all sub-tasks it is called sequential, whereas when all the tasks depend on a common sub-function while still being independent from each other it is defined parallel. (Stone, Wood, & Crawford, 1998)

The heuristic method comprehends three distinct approaches, all relying on the same flow basis.

1. **Dominant flow**: groups in a module all the sub-functions a flow encounters before leaving the system or being converted in a different kind of flow. (Stone, Wood, & Crawford, 1998)

![Dominant flow heuristic](image)

Figure 23 - Dominant flow heuristic applied to a generic function structure (Stone, Wood, & Crawford, 1998)

2. **Branching Flows**: modules correspond to branches of parallel function chains. With this approach the product architecture enables component swapping and bus modularity (Stone, Wood, & Crawford, 1998)

![Flow branching heuristic](image)

Figure 24 - Flow branching heuristic applied to a generic function structure (Stone, Wood, & Crawford, 1998)

3. **Conversion-Transmission Modules**: combines in a module conversion sub-functions or conversion-transmission pairs, i.e. those sub-functions which take as input a certain type of flow and turn it into another form of output flow. (Stone, Wood, & Crawford, 1998)
Figure 25 - Conversion-transmission applied to a generic set of sub-functions

Downsides that prevented the choice of this method:

- the modules identified differ depending on the approach chosen
- “each of the methods may identify overlapping modules or modules which are subsets or supersets of other modules” (Stone, Wood, & Crawford, 1998)

![Diagram showing conversion-transmission applied to a generic set of sub-functions](image)

Figure 26 – Example of the confusion in the choice between modules identified with the 3 heuristic approaches in the example of a SKIL Twist power screwdriver, adapted from (Stone, Wood, & Crawford, 1998)
**Design structure matrix**

The Design Structure Matrix is a network modelling tool used to recognise modules in the system structure from groups of elements that have more internal than external interactions. (Eppinger & Browning, 2012) (Albers, Burkardt, Sauter, & Sedchaicharn, 2008)

The DSM is represented as a square N x N matrix, mapping the interactions among the set of N system elements. (Eppinger & Browning, 2012)

The DSM can be applied to several types of systems (product, organization, process), in the case of product architecture modelling “the elements would be the components of the product and the interactions would be the interfaces between them” (Eppinger & Browning, 2012).

The components are labelled in the leftmost column and the top row and the relationships between them are marked in the corresponding off-diagonal cells.

![Design Structure Matrix](image)

**Figure 27 - Example of binary DSM (a) and its equivalent in diagraph form (b) (Eppinger & Browning, 2012)**

Each off-diagonal mark in the matrix represents the output of the element in the corresponding column and the input of the element in that row, so proceeding column by column all the outputs of the heading element of the column can be seen while examining each row all the inputs to the heading element of the row are represented.

The main advantage of the use of the DSM method is the ease of understanding, which thanks to the graphic representation in matrix form allows to represent even complex architectures in a compact and “intuitively readable” way. (Eppinger & Browning, 2012)

A confirmation of this fact can be seen comparing the DSM above with the chart below representing the same structure in an evidently less effective way.

<table>
<thead>
<tr>
<th>Element</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td>E</td>
<td>D, F, G</td>
<td>H</td>
<td>A, B, F</td>
<td>B</td>
<td>E</td>
<td>C</td>
<td>E</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td>D</td>
<td>D, E</td>
<td>G</td>
<td>B</td>
<td>F, H</td>
<td>B, D</td>
<td>B</td>
<td>C</td>
</tr>
</tbody>
</table>

Table 2 - Chart relationship representation

In the example the interactions were classified just as present or absent, but in different types of DSM charts the relations can be indicated by a numerical or symbolic weighting factor representing the number of relationships or their importance.
Theoretical background

The technique to recognize the modules in the product structure through the analysis of the DSM is called clustering and consists in reordering the rows and columns to maximize the number and importance of interactions between adjacent elements in the DSM (Eppinger & Browning, 2012). The goal of the clustering process is to isolate modules that have as many relationships as possible within them and as few as possible between them, so several iterations may be required.

The two main key factors that must be carefully balanced for a successful outcome of the modularization process are the dimensions of clusters and the number of interactions outside them. Eppinger and Browning (2012) indeed propose the following expression for the objective function to be minimized for the clustering analysis:

\[
Obj = \alpha \sum_{i=1}^{M} C_i^2 + \beta I_o
\]  

(1)

Where \( C_i \) is the size of the cluster, \( I_o \) the number of outer interactions and \( \alpha \) and \( \beta \) weighting factors.

Additional aspects to be considered comprehend:

- Interaction types: interactions can be traced back to four main types (spatial proximity, material flow, information flow and energy transfer) and depending on the relative weight given to each of them, different sets of clusters can be individuated for the same structure. (Eppinger & Browning, 2012)
- Integrating elements: elements that remain unassigned to any of the clusters due to the variety of components they interact with act as integrative components in bus modularity architectures (Eppinger & Browning, 2012)

![Figure 28 - Composite DSM including spatial, energy, information, and material interactions (left) compared to its clustered form (right) (Eppinger & Browning, 2012)](image)

Downsides that prevented the choice of this method:

- heavily influenced by the importance attributed to each type of interaction, generating results not consistent over time (Eppinger & Browning, 2012)
- overlapping clusters (Eppinger & Browning, 2012)
- even though it is always possible to manually rearrange the elements, for the clustering to be effective complex systems require the use of commercial software or macros. (some examples on DSM Conference (2019))
3 Method and implementation

3.1 Research design

To perform the study commissioned for this thesis work, the research course represented in the flowchart below has been followed.
The research object of this paper has been carried out adopting an interpretivist approach, grounded on the collection and subsequent analysis of data to derive rules and knowledge. Interpretive approaches rely on inductive reasoning to gain understanding (Kroeze, 2012) “in areas with no or insufficient a priori theory” (Bhattacherjee, 2012). In contrast with positivism, where research questions are used for theory testing, the inductive approach uses them to “narrow the scope of the study” (Gabriel, 2019). In this method, the research work, starting from data, aims to build “a theory about the phenomenon of interest from the observed data” (Bhattacherjee, 2012), consequently this research work can be divided in three main stages:

1. Prestudy
2. Data collection
3. Data analysis

For each of which several methods and techniques (described more in detail later on in this chapter) have been employed.

The term prestudy refers to the gathering of background information necessary to frame the research and provide directions for the way forward, before getting into the central theme of the paper. The first step, once established the purpose of the project, was the acquisition of a general view of the context of the research work, i.e. the concepts of modularization and standardization and their implications.

For this reason, even before physically being in the company, an extensive literature research has been carried out to gain an insight on the existing approaches to the topic, inspecting relevant publications, websites and course literature.

Once in the company, another piece of background information necessary for the project has been collected: the external perspective. As prompted by Schuh, Rudolf and Vogels (2014) the market analysis was used to identify the initial field of observation and market segments. This investigation comprehends technical similarities with competitors, customer fields, new competitors and innovations as well as price ranges, regions and usage. (Schuh, Rudolf, & Vogels, 2014)

The next phase was the collection of data directly significant for the scope of the research. The material gathered concerns all stages of the of the product development process: identification of customer needs and expectations, commercial offer and definition of the architecture of the system. The sources were respectively clients and the company’s employees dealing with them, historical records of Ficep’s commercial offers and dossiers on handling systems already realized and Ficep’s experienced product managers and designers in cooperation with Trennitalia’s expertise and knowledge. The methods used in this process were brainstorming, to obtain the full spectrum of customer requests straight from the interested parties, case studies and interviews, to look for patterns in the translation of the requests into technical specifications of the system, the relationships between technical specifications and physical characteristics of the elements of the handling system and the rules for their configuration.

All the information assembled in the previous phase was then analysed with the scope of deriving a new product architecture. The methods used in consecutive order were functional decomposition to subdivide the functionalities of the whole handling system into functions of the individual units that make them up, Function-means tree analysis to assign the functions to constituent modules, the interface analysis through which the interdependencies of the modules are used to standardize the interfaces between them to guarantee interchangeability and set the performance to remain the same.

To structure this knowledge a configurator has been created using Excel as base software and, being the distribution of translator arms a linear optimization problem, the built in Solver tool has been included in the computation routine. Automatizing the definition of constraints (self-adapting on the base of the input specifics) and launch of the solver through the coding of macros allowed the individuation of the optimal centre distance, in turn instrumental for the choice and layout of roller conveyors.
3.2  Prestudy

3.2.1  Literature research

The first stage in a research project is the definition of the context and the background for the study and the best way to start gaining acquaintance with the topic is to perform a literature research on it. This procedure involves analysing and synthesizing the conceptual literature as well as articles, completed research reports, theses, conference papers and all the relevant material about the topic under investigation (Williamson, 2002). Exploring the information directly connected to the topic of the study can also widen the horizons of the researcher, leading to serendipital discoveries beyond the specific field of study and uncover links between subjects useful in the subsequent practical applications of the theory examined. (Williamson, 2002)

The exploration of the topic in literature includes the selection and articulation of the research questions to be investigated in relation to the object of interest of the research. All actions from that point onward will indeed be aimed at seeking answers to the research questions chosen. (Bhattacherjee, 2012)

Unlike positivist approach, in which the research questions are formulated as hypotheses to be validated using empirical data, in interpretivist research designs the research questions state the area in which new theory will have to be derived from data (e.g. what, why, how, when, etc.) (Bhattacherjee, 2012).

3.2.2  Market and competitors’ analysis

Ficep customers are either builders of structural steel structures that work on contracts for large infrastructure projects and carry out the entire process, or their subcontractors, outsourcing partners specialized in carrying out the machining of beams and profiles they are subcontracted for.

The main applications can be:
- Industrial buildings
- Residential buildings (skyscrapers)
- Other public buildings (e.g. stadiums, arenas, etc.)
- Offshore structures
- Telecommunication towers and transmission infrastructures
- Bridges and other major infrastructures

![Figure 30 - Examples of Ficep customers' applications (courtesy of Ficep)](image)

Ficep's reference market is mainly foreign, where over 90% of turnover is realized, and extra-European where 80% of turnover is realized. It is therefore important to investigate the situation of the competitors on a global scale.
The metalworking machinery sector appears to be stable worldwide, all the main competitors produce carpentry CNC machines and plants, specifically for the processing of beams, corner pieces and sheets. The most relevant are:

- Voortman (Netherlands)
- Vernet (France)
- Kaltenbach (Germany)
- Geka (Spain)
- Daito (Japan)
- Peddinghaus (USA)

According to the information on the market sharing retrieved by the company, the three closest competitors in terms of turnover result to be:

<table>
<thead>
<tr>
<th></th>
<th>Turnover 2011</th>
<th>Net Worth Capital</th>
<th>Employees in Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaltenbach</td>
<td>58 ml</td>
<td>9,5 ml</td>
<td>500</td>
</tr>
<tr>
<td>Voortman</td>
<td>28 ml</td>
<td>6,2 ml</td>
<td>125</td>
</tr>
<tr>
<td>Vernet</td>
<td>17 ml</td>
<td>3 ml</td>
<td>118</td>
</tr>
<tr>
<td>SUBTOTAL</td>
<td>103 ml</td>
<td>18,7 ml</td>
<td>743</td>
</tr>
</tbody>
</table>

Compared to Ficep’s data:

<table>
<thead>
<tr>
<th></th>
<th>Turnover 2011</th>
<th>Net Worth Capital</th>
<th>Employees in Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Competitors</td>
<td>103 ml</td>
<td>18,7 ml</td>
<td>743</td>
</tr>
<tr>
<td>Ficep</td>
<td>107 ml</td>
<td>75 ml</td>
<td>380</td>
</tr>
<tr>
<td>TOTAL</td>
<td>210ml</td>
<td>93,7 ml</td>
<td>1123</td>
</tr>
</tbody>
</table>

The development goals set for the Smart Modular Steel Fabrication System project are intended to gain a significant further advance over the state of the art in the sector, in terms of performance and functionality.

The structural steel manufacturing field has in recent years seen a strong technological development that has led producers to offer ever more sophisticated and performing machines, able to perform more operations without the need to move the semi-finished part from one piece of equipment to another and without the use of highly qualified personnel. Traditionally, in fact, cutting (normally thermal) and processing activities (drilling, milling, marking) were performed on different machines, at different times and with personnel with different qualifications. In the last decade, however, factors such as: the increase in the value of semi-finished materials, and consequently the value of the warehouse, the reduction of time between design and construction, the race for efficiency through “just in time” also for non-series productions, such as those in the construction sector and heavy carpentry, have progressively led the market to demand increasingly high-performance solutions from manufacturers, characterized by high automation and productivity, combined with greater flexibility and versatility in production systems.

From the information available, no competitor has yet developed a fully modular configuration system that covers the entire machinery and handling systems.
Method and implementation

3.3 Data collection

3.3.1 Brainstorming

Brainstorming is an idea generation tool used in groups to combine a relaxed, informal approach to problem solving with lateral thinking. The strength of this method is the possibility of generating a large number of ideas about a specific topic in a short time. Unlike other more structured and analytical processes this approach encourages creative thinking and stimulates enthusiasm, encouraging active participation. (Kohlweiss & Herstätter, 2018) (MindTools, 2019)

The base rule for Brainstorming is “Quantity before quality” as each participant should work for quantity and all proposals should be taken note of without criticism or comments (neither positive nor negative) that could shut off the flow of ideas. (Kohlweiss & Herstätter, 2018)

Every single idea can thus become the starting point for all the other participants to go further in that direction and / or take it to the next level. Only after a satisfactory number of answers has been collected, it is possible to engage a constructive discussion of all the suggestions to evaluate and choose between them.

The most important aspect of this practice is the separation in time of stream of thoughts and critical analysis, as people tend to immediately evaluate each suggested idea their own, as well as others, while postponed assessment encourages interaction between team members. (Kohlweiss & Herstätter, 2018)

Another essential factor for a fruitful outcome is the choice of heterogenous group participants, coming from a wide range of disciplines and with different points of view on the topic, for example including customers, that in this way would even get a feeling of being more committed in the partnership as they were involved in the development process. (MindTools, 2019)

Ficep has recurred to this method in a workshop with about 40 people (including sales agents, customer care and customers) from all over the world divided in 6 mixed groups to bring into focus the definition of the functional specifications of the system in terms of performance, functionality, versatility and flexibility requirements.

![Figure 31 - Brainstorming session set (courtesy of Ficep S.p.a.)](image)

The subjects under discussion were the general situation of the market distinguishing political and economic drivers, steel construction trends, Ficep strengths, weaknesses and opportunities compared to competitors.
3.3.2 Case studies

Case study research is a valid method for theory development and testing, as it provides evidence in areas where existing knowledge is limited. This approach is indeed particularly appropriate when the "experiences of individuals and the contexts of actions are critical" or when "a phenomenon is dynamic and not yet mature or settled" (Williamson, 2002). In order to handle more easily the amount and variety of the data of interest, the latter have to be structured in a way that will facilitate the recognition of trends, for example with the use of tabulations. (Williamson, 2002)

The commercial offers of the whole carpentry product range with standard configuration handling system has been summarized in an Excel file to be used later in the deduction of the recurring patterns in the assembly of the rollerways and loading / unloading tables with respect to the specifics of the machine tools present in the plant and their eventual combination. The study of the layouts and part lists of plants realized in the past by Ficep and currently on duty has been used in the testing the configurator to compare the results proposed by its calculations with known feasible solutions to check their appropriateness and consistency.

3.3.3 Interviews

The interview technique is commonly used in surveys where the information sought cannot be articulated in simple brief answers. Due to the direct personal contact interviews are properly fitted for exploratory purposes concerning a specific topic, since conducting them in an unstructured o semi-structured way basically lets one answer lead to the following questions. (Williamson, 2002)

They are often used to “collect extensive data from key people” about case studies, going in depth about specific points of interest (Williamson, 2002)

Several meetings have been scheduled with the partner company Trennitalia, with mutual visits in both facilities to get more complex and complete responses about the findings of the case studies and refine the theories deducted. Despite the objective expense in terms of time and money, the answers obtained through the semi-structured interview with Eng. Riccardo Borsoi, have been well worth the investment.
3.4 Data analysis

3.4.1 Functional decomposition

The customer needs identified in the previous steps have to be structured and transformed into formalized and detailed specifications that describe what the functionalities of the individual units and of the complete production system must be. The design of the modular architecture follows a functional approach, i.e. by breaking down the machine on the base of function of use criteria. This approach is more innovative than the morphological-structural approach traditionally used, which relies on technical-structural canons and essentially concerns functions related to the form and location of the modules. The process of deriving the individual modules specifications starting from the general specifications of the system will have to bear in mind the importance of compromise, as too strict specifications can lead to an excessive cost of the individual modules. In general, the process presents different problems depending on the type of parameters implied in the specification. In fact, while some overall characteristics refer directly to the characteristics of the modules, most of them depend on the overall architecture of the system. In the first case the specification values can be directly transferred from the list of total specifications to the list of specific details of the functional units, while in the second the procedure is more complex. For example, feed rates move directly from the list of overall specifications to the list of drive unit specifications, while the projection of the dynamic characteristics depends on the type of module. The static force that stresses the system during the translation of the beam, affects in different ways rollerways and loading / unloading tables. The determination of the necessary stiffness of the system regarding this stress is therefore based on completely different principles, as in rollerways is controlled through the diameters of the rolls while in the loading / unloading tables is responsible for the type and number of translator arms.

This example shows how the projection process of the list of overall features in the list of module characteristics can be a complex process since:

- The value that measures the overall performance can be a non-linear function of the value that measures the performance of the module;
- This function may depend on the type of machine;
- The nature of the service to be specified and the physical size of the value that the specification could change, passing from the overall performance to that of the module (for example in the case where the bending rigidity of the overall system results in a torsional rigidity of the module).

The characteristics of the modules can be classified into three different types that require different attention with regard to the decomposition process:

- **Independent characteristics**: they concern elementary or basic functions that refer to a single module. In this case the value of the global specification is transferred directly to the list of module specifications. In general, the number of independent features in the case of a morphological-structural decomposition tends to be much smaller than in the case of a functional breakdown. For example, in the case of a slider, a morphological-structural breakdown leads to identifying the static part and the moving part of the slider as modules. Consequently, the global specification relating to positioning accuracy results in a number of different specifications for the two component modules. On the other hand, a functional decomposition leads to the identification of the entire axis and the positioning precision can be transferred as it is to the functional module.
• **Dependent characteristics**: they derive from global characteristics while maintaining their nature as they are transferred in the list of the specifications of the individual modules. In this case the values to be specified for the various modules can depend significantly, and also in a non-linear way, both from one another and from the type of machine. The mapping of the values of the global specification in the specification values of the various modules involves an optimization activity aimed at obtaining high overall performance while maintaining the performance of the individual modules relatively low, to make them more economical.

• **Abstract features**: they occur when the characteristics of each constituent module, such as reliability, although derived from the global specification, are of a different nature. In the modular functionality the abstract features describe aspects of the production system of a global nature such as flexibility and reliability.

The objective of the process is to minimize the number of dependent or abstract features. In these cases, in fact, the derivation of the module specifications requires more elaboration.

3.4.2 Function-means tree analysis

"The function-means tree is a method of modelling a product by the systematic decomposition of functions based upon the law of Hubka (1988), which states there are causal relations between functions and means." (Robotham, 2002)

This method consists in the structuring with a tree representation of:

- Functions: verb describing the task WHAT
- Means: element or subsystem that performs the task HOW

Starting from the main function of the product, each function in the functional decomposition is assigned to a mean proceeding top down, following causal relations. (Robotham, 2002)

This method is also able to handle the presence of variants of the same product in which a function can be realised by different means, for example in the context of this research work loading / unloading tables can translate the beams by means of catchers or carts.

To keep track of the decision take in the definition of the final product architecture it's advisable to colour the mean(s) chosen between the possible alternative ones. The definitive function-means tree will be rid of the discarded solutions and will represent the final structure of the product divided in modules.

![Function-means tree analysis](image)

Figure 32 - Principle structure of function-means tree showing alternative solutions and a candidate solution (Robotham, 2002) (Hubka & Eder, 1988)
3.4.3 Interface analysis

The design of the interconnections between the modules requires an accurate control of the interdependencies between them in such a way that does not compromise the achievement of the overall performance of the system. During this process a list of specifications has be defined for each functional unit to ensure that the modules can be integrated and that the machine or the resulting system possess the required performance. The information to be transferred does not only concern the characteristics of the module's functionality but also the interdependencies with the other modules. These can be of three types:

- geometrical interdependencies: they concern the position of objects belonging to the module in question with respect to the position of objects belonging to other modules (for example the position of the tool change affects both the spindle unit and the tool exchange unit)
- logical interdependencies: they concern the communication protocols, the type of signals etc, which allow the various modules to communicate with each other and with the control unit
- physical interdependencies: they concern the different connections (mechanical, electrical, hydraulic) that must be established between the modules

This activity is all the more important talking about specifications intended for a supplier who has been entrusted with the construction of a module, as in the case of the supplier of the handling systems.

3.4.4 Linear Optimization

Linear Optimization is a problem-solving method used to sort out the maximization or minimization of linear functions subject to linear constraints.

The function to be maximized (or minimized) is called the objective function (Ferguson, 2019).

Two variables linear optimization problems are easily solvable graphically, while for higher numbers of variables calculators are needed to find the feasible solutions once objective function and constraints have been defined.

The Solver is a built-in add-in tool for Microsoft Excel, useful for the resolution of optimization problems. It looks for an optimal solution (maximum, minimum or equal to a set value) for a formula in the objective cell, by adjusting the values of decision variable cells (from which the value of the objective cell depends) subject to constraints. (Microsoft, 2019)

For the scope of the work, this tool was used in the configurator to calculate the optimal distribution of the loading / unloading tables’ arms, formulating the optimization problem as a knapsack problem.

Figure 33 - Knapsack problem depiction (Terh, 2019)
This kind of combinatorial problem can be explained with the example of a knapsack with maximum capacity $W$ and $N$ items to fill it with, each one with his own weight $w$. The objective is to maximise the use of the knapsack capacity by varying the quantity of each item as follows.

**Objective function:** Total weight of the items in the knapsack

\[
\text{Total weight} = n_1 \times w_1 + n_2 \times w_2 + n_3 \times w_3 + n_4 \times w_4 + n_5 \times w_5 + (\ldots)
\]  

(2)

The goal is to maximise that function by varying the decision variables, i.e. the number of items of each kind ($n_1$, $n_2$, $n_3$, $n_4$, $n_5$, ...)

The constraint in this basic case is only on the objective function and its dictated by the physical limit of the knapsack capacity.

The results of this combinatorial process will be the optimum value of the objective function as well as the number of items of each kind.
4 Findings and analysis

In line with the interpretivist approach, the research was conducted following inductive reasoning: collecting and analysing data to develop concepts, insights and understanding from the patterns of the data. (Williamson, 2002) citing (Reneker, 1993) The understanding of the topic acquired in the prestudy through literature research and market analysis has been used to formulate the research questions to guide the research path towards the development of theory regarding the final goal of this work, a method for the optimization of general product architectures through modularization and standardization, and its application to the specific case of Ficep's handling systems. (Williamson, 2002) The empiric nature of the aim of this work suits perfectly the definition of grounded theory, which literally means “built from the ground upwards, from data observed and collected in the field”, hence the need for data analysis throughout the project not just in the concluding stage. (Williamson, 2002) The observation of patterns in data, however, is not sufficient for the creation of a new theory unless the causes behind these trends can be explained. (Bhattacherjee, 2012) Albeit keeping a generally open attitude towards collateral aspects of the topic to be investigated that may arise during the process, the first step in every journey is the setting of the route of the research towards the final target. Consequently, the beginning of the operative work consisted in the collection of customer needs and expectations about the final product commissioned. These results were then translated, with the help of the supplier and Ficep's experienced employees, into specifications of the system, i.e. the input values for the calculations behind the choice and configuration of the handling system's components. Through analysis of case studies and interviews the effects of the variations of these independent variables (the input values obtained in the preceding point) on the overall structure of the elements of the system a first draft of configurator for these characteristics has been developed. This first calculation tool though, had the limit of being dependent on the specific standard profiles and was unable to handle generic sections. To be able to configure even the optimal inner structure of roller conveyors and loading / unloading tables, a deeper understanding of the subdivision of their functions into their parts was necessary. A functional decomposition analysis was performed for each of the elements and the resulting subfunctions have been assigned to specific modules through a function means tree analysis. At this point the links between the composition and structure of the whole plant and the conformation of the elements of the handling system were studied, individuating dependencies, correlations, compatibilities and incompatibilities. The charts derived have then been used as tool for the generation of a proper Configurator for the whole handling system, able to elaborate input data from the customer requests to configure the overall structure of the system (type or loading / unloading tables, number of translator arms, number and type of roller conveyors and all the positionings) as well as the internal structure of its components (presence or absence of each accessory component) adapting it in real time and in standardized ways consistent from time to time. The level of detail reached with the Configurator made it possible to associate to each standard submodule its cost, therefore making it also an accurate calculator for the costs of each unit. This inspired the decision to use it also as tool to study the trends for costs associated with variation of linear weights and lengths and confront it with the ones obtained with standard values. All the steps taken in the process constitute a method for product modularization and standardization suitable for any kind of product.
The final product is grounded on the following intermediate results, that all together constitute the steps of the method proposed in this work for the revision of general product architectures in modular and standardized key.

4.1 Collection of customer requests

The workshop organized for carefully selected sales agents, customer care and customers coming from several countries has provided a good insight on how the current political and economic situation is perceived around the world and how could this reflect on the market, with particular attention to the structural steel production sector. The focus has then moved to the steel construction trends and how Ficep and competitors keep up with innovation, laying special attention on the comparison between the company state of the art offer with what is available on the market. During the discussion after the brainstorming all contributes have been presented to the groups gathered in the conference room for evaluation and a more in-depth analysis to sort out the most relevant observations and suggestions on each topic.

The commercial offers of the entire carpentry range with handling system in standard configurations have been summarized, analysed and tabulated to be used later in the deduction of the recurring patterns in the assembly of roller conveyors and loading/unloading tables in relation to the specifications of the machine tools present in the plant and their possible combination.
4.2 Translation of customer requests in technical specifications of the system

Working in collaboration with Trennitalia, supplier of the handling system, starting from a historical analysis of orders, customer requests have been translated into system specifications, which have been reduced to the list below:

- Manufacturing process → Machine(s) Type and Auxiliary Machines
- Profile to be machined → Linear weight, Width, Length, Short pieces
- Structure of the plant → Perpendicular transl. length, Unloading Side

4.3 Effects of the technical specifications on the structure of the handling system

The specifications obtained were then assigned to the relevant handling components, identifying the relationships between technical specifications and physical characteristics.

<table>
<thead>
<tr>
<th>System configuration</th>
<th>Rollerways</th>
<th>Loading /Unloading Tables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Machine(s) Type</strong></td>
<td>specific rollerways for each kind of machine tool on the output side e.g. liftable rolls with sawing machines</td>
<td></td>
</tr>
<tr>
<td><strong>Auxiliary Machines</strong></td>
<td>specific rollerways for each kind of machine tool on the output side e.g. rollerways for magnet</td>
<td></td>
</tr>
</tbody>
</table>
| **Linear weight**    | • diameter of the rolls  
|                      | • different support structure | • number of arms  
| **Width**            | • roll length  
|                      | • structure width | • size of the loading / unloading tables |
| **Length**           | number and distribution of rollerways | • number of arms  
|                      | • size of the loading / unloading tables |                       |
| **Short pieces**     | increase in number of rolls | increase in number of arms |
| **Perpendicular distance to cover** | Length | loading /unloading tables width |
|                      | **Side** | positioning of loading /unloading tables |

Table 3 - Effects of the technical specifications on the structure of the handling system
To investigate the dependencies of the structure of the handling system with respect to the specifications of the workpieces, a first spreadsheet was drawn up with all the standard structural steel profiles currently on the market.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Width</th>
<th>Length</th>
<th>Machine Tool Sizes</th>
<th>Roller Diameter</th>
<th>Number of Arms</th>
<th>Number of Motors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 35 - First configurator interface (section)

The file, taking as input usable width and length of the beam (in red), is able to calculate for each profile the sizes of machine tools with which it can be worked, diameter of the rollers mounted on the roller unit and number of arms and motors for every type of counter.
The configurator is able to calculate the overall structure of each loading / unloading table type (number of motors and translator arms) and the structure of the roller conveyors (length, diameter and thickness of the rolls).

This first version of configurator was realised avoiding the use of macros, so despite guaranteeing the generation of the basic values of interest, this choice implied some functional limitations.

For example, to bypass recursive calculations in the same cell (not possible using just the software formulas) the number of translator arms for each type of table is indicated as the number of additional arms necessary for each of them.

The theoretical number of translator arms depends in the first instance on the length of the profile to be moved but following Trenitalia’s suggestion a further aspect has been taken into account, using additional translator arms to adapt loading / unloading tables with carts even of sizes of inferior weight capacity.

The theoretical number of translator arms (regardless of the type of loading / unloading table) is calculated in the corresponding cell as:

\[ Number\ of\ theoretical\ translator\ arms = \text{int} \left( \frac{\text{beam length} - L}{\alpha} \right) \]  

(3)

Where \( L \) is a fixed length and \( \alpha \) a constant value.

Then in the cell below each type of translator arms the configurator checks if the total weight of the beam to be handled split on the theoretical number of translator arms falls within the working range characteristic of each loading / unloading table type.

\[ IF \left( \frac{\text{beam linear weight} \cdot \text{beam length}}{\text{number of theoretical translator arms}} \right) < \text{maximum weight per tr. arm} \]  

(4)

If the condition is verified an X is shown in the cell, if not, the computation is repeated incrementing the number of arms up to a fixed number displaying the number of additional arms that satisfy the condition. In case even the use of further translator arms does not match the condition, the cell remains empty indicating that there are no feasible solutions for that specific loading / unloading table type.

Loading / unloading tables with catches on the other hand can be opted for in wider working ranges by adding auxiliary motors, once again in the same way as for loading / unloading tables with carts, the cell below each type is filled for viable solutions with either an X or the number of necessary additional motors.

This early version of configurator focuses on the overall structure of the handling system, taking into account only the choice of its components, without providing information regarding their relative position for layout of the exact subdivision of the conveyors that compose the rollerways.

Another limitation of this type of configurator lies in its dependence on the geometry of the profile and the lack of ability to respond to problems related to the geometry of custom profiles, so in order to achieve the final objective, a deeper analysis of the structure of the system was necessary, investigating the connections between the mechanical and physical properties required by the specifications and their allocation in the modules of roller conveyors and benches.
4.4 Product architecture

The functions derived from customer requests have been translated into functions and associated to physical elements through function means tree, starting from the complete handling system, and proceeding top down to subassemblies and components.

The loading / unloading tables product architecture has the following structure

Figure 36 - Loading / unloading tables product architecture
While for the roller conveyors:

Figure 37 - Roller conveyors product architecture
4.5 Rules for configuration of the handling system and its components

The handling system depends on the type and number of machine tools the customer needs to carry out the manufacturing. Below some examples of the ways the types of machine influence the choice of the structures for the roller conveyors closest to the machines.

![Diagram showing examples of changes in handling system's configurations to varying of the working machines](image)

Figure 38 - Examples of changes in handling system's configurations to varying of the working machines (courtesy of Ficep S.p.A.)

Taking the drilling machine layout as standard is then evident that when the machine is for example a saw, in order to enable the rotation of the moving part equipped with the blade, the roller conveyors will have to be angled and liftable not to block it. Furthermore, when the machining processes to get the finished product have to be performed by more than one kind of machine, as happens in most cases, the plants become combined. Once again, the roller conveyors closest to and in between the machines will have special structures.
Defining the type of machining that must be performed is still not enough though, as depending on the dimensions of the profiles to be machined the handling system will have to adapt its configuration to suit every specific case. The simplest case is the one of drilling machines where the choice of number of translator arms and roller conveyors width is directly derivable from weight and overall dimensions of the section of the profile. For sawing machines instead, the roller conveyor structure will have to consider the different degrees of rotation the different sizes of machines are able to perform. Below a visual summary of the rules derived for this case.

Figure 39 - Different types of liftable roller conveyors depending on the size of the saw in the plant (courtesy of Ficep S.p.A.)
Moreover, even the length of the beam to be handled influences the structure of the system components and their disposition, as can be seen in the example below comparing the layout for standard length pieces (top) and the one for the handling of short pieces (<2500 mm) (bottom).

Figure 40 – Differences in the configuration of the handling system when short pieces have to be moved (bottom) compared to normal length pieces (top) (courtesy of Ficep S.p.A)
After having established the overall structure of the handling system by defining the number of translator arms for each type of loading / unloading table and the usable width and roll diameter for roller conveyors on the base of mechanical structural analysis, the rules for assembly of the optional feature have been retraced and structured similarly to product variants charts.

Reading down each column it is possible to see the optional components that will be mounted on the basic structure for the case corresponding to the heading of the column.

For the loading / unloading tables the decisive factor for the choice of the optional components is the type of table.

Table 4 - Loading / unloading tables rules for options’ configuration chart

<table>
<thead>
<tr>
<th>Catches</th>
<th>Carte</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>QTG1</td>
<td>QTG6</td>
<td>QTG7</td>
</tr>
<tr>
<td>ALZATA INTERMEDIA</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>BATTUTA ALLINEAMENTO A RULLO</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>CANALINA PARA CAVI AL METRO</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>LIMITATORE DI COPPIA</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>LUNGHEZZA CARDINO COMPRESSA TRA 1050 e 1950 mm</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>MOTORIZZAZIONE 4472 kW PER QTTH6</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>MAGGiorAZIONE MOTORIZZAZIONE 2,2 kW X INVERTER</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>MOTORIZZAZIONE STANDARD 1,8/1,2 kW</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>MOTORIZZAZIONE STANDARD 2,3/1,6 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOTORIZZAZIONE STANDARD 4,4/3,3 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VALVOLA DI BLOCCO PILOTATA</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 5 - Roller conveyors rules for options’ configuration chart

<table>
<thead>
<tr>
<th>Standard Rollerway</th>
<th>Powered Rollerway</th>
<th>Magnetic Pressure</th>
<th>Bidirectional Load/unload</th>
</tr>
</thead>
<tbody>
<tr>
<td>BATTUTA ALLINEAMENTO A SCOMPARSA CON RULLO Ø 62 mm</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>CANALINA PARA CAVI AL METRO</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEVIAZIONE CATENA 600</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>DEVIAZIONE CATENA 1200</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>DEVIAZIONE CATENA 1800</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>FINE CORSA INERTIO (SENZA CAVO ELETTRICO)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FINE CORSA MECCANICO</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>MOTORIZZ. A BORDO PER INV. CAV. H (0,35 kW)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOTORIZZ. FICEP PER INVERTER (2,2 kW)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOTORIZZ. FICEP PER INVERTER (4 kW) con ventilazione</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPINGITORE STANDARD</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPINGITORE ZONA MAGNETE</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MONTAGGIO SPINGITORI</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>TRASMISSIONE INTERM. 600</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRASMISSIONE INTERM. 1200</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.6 Configurator

All the previous results of the project have been implemented in the creation of a dynamic configurator to be used as an automatic tool for the reorganization and optimization of the architecture of the entire handling system.

The configurator, starting from the specifications requested by the customer, is able to calculate and propose the user all the feasible solutions to that specific problem, customizing the layout and composition of the elements by choosing the best combination in the assembly of the standard modules that make them up.

![Configurator user interface](Figure 41 - Configurator user interface)

Compared to the previous version, the inputs are not only related to the profile to be machined but it considers the structure and composition of the plant as well. This further information allows the worksheet to calculate the relative positions of the elements of the handling system and their architecture.

The upper part of the user interface is designated for the definition of the problem, filling the coloured cells with the data necessary to feed the calculations. To guide the input process the cells have been colour coded, with bright yellow indicating cells where values have to be typed, while light blue cells marking drop down menus. All input values are validated, and a macro has been coded to turn red the cells whose value is not acceptable and/or does not make sense.

To set up the layout problem in the configurator, the user has to choose the plant configuration, from the top right table (red arrow number 1): single machine tools (drilling, sawing, thermal cut) or combined (drilling-sawing, drilling-thermal cut) and the eventual complementary machines (marking machine and, when a saw is present, magnet and short pieces conveyor, otherwise hidden).

Process parameters must be declared in the top left chart (red arrow number 2), i.e. linear weight, roller conveyors width, beam length, perpendicular translation length,
Findings and analysis

short pieces handling, roller conveyor motorization, opposite unloading side, all divided in loading (left column) and unloading side (right column).

By means of the drop-down menu in the top cell of this chart it is possible to choose between metric or imperial measurement system for the values inserted, while the white chart on its side is automatically filled with the values converted in the other reference system, letting the user always be aware of both formats of the values.

With this data the configurator populates the charts directly below corresponding to loading (blue arrow 1) and unloading tables (blue arrow 2) with the information corresponding to the feasible solutions (as in the previous versions of the configurator) and their respective prices.

These prices are divided into price for standard and custom structures of the loading / unloading tables (i.e. with standard or custom perpendicular translation lengths), and the accuracy of the assessment is possible thanks to the background configuration of each type of table complete with the optional extras required for that specific plant layout.

The cells corresponding to the type chosen will be highlighted matching the headings of the loading/unloading tables.

Given all the input information to the configurator pressing the big bright yellow button “CALCULATE” the executable is launched.

The macro coded in VBA checks if the Excel solver is active, and in case of negative answer proceeds to activate it, then checks if there are any red cells (non-acceptable values), and in positive case gives an error signal.

After these verifications it sets up the parameters for the optimization problem for the layout of table’s arms, calculating the centre distances between them and pasting the values in the white small charts next to the corresponding loading / unloading table chart.

<table>
<thead>
<tr>
<th>LOAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam length</td>
</tr>
<tr>
<td>n° of arms</td>
</tr>
<tr>
<td>step dimension</td>
</tr>
<tr>
<td>table length</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decision Variables</th>
<th>x1</th>
<th>constraint</th>
<th>delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>10</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>c</td>
<td>12</td>
<td>3600</td>
<td>3600</td>
</tr>
<tr>
<td>d</td>
<td>12</td>
<td>3600</td>
<td>4200</td>
</tr>
<tr>
<td>e</td>
<td>12</td>
<td>3600</td>
<td>4200</td>
</tr>
<tr>
<td>f</td>
<td>12</td>
<td>3600</td>
<td>4200</td>
</tr>
<tr>
<td>g</td>
<td>12</td>
<td>3600</td>
<td>4200</td>
</tr>
<tr>
<td>TOTAL</td>
<td>15600</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 42 - Setting of the optimization problem parameters behind the configurator’s calculation

Considering that the intervals have to be multiples of 300 mm, this value has been set as step size and the intervals as the products of the decision variables multiplied by the step size. The objective function to be minimized is the delta between the beam length and the sum of the centre distances (table length).

All centre distances are constrained to be positive, smaller than the values in the constraint column and less than or equal to the following centre distance.

When launched, the solver updates the initial numeric data contained in the decision variable cells, to find the optimum solution to the objective cell, containing a formula that recalls the data of the variable cells.

Once the solution is found, the results produced by the solver’s calculations corresponding only to the centre distances present in the case under analysis are copied back to the master interface.
After the characterization of the centre distances, the roller conveyors composing the rollerways are defined. The choice aims at using structures that fit inside the centre distance while at the same time maintaining a fixed distance between each group and the following one (blue arrow 3 and blue arrow 4). In the figure below a visual explanation of the ON/OFF logic used to layout the roller conveyors in between the table’s arms: the roller conveyors possible positions are schematized as blocks of fixed dimension that are turned off (hatched in the picture below) when they are crossed by a table arm. The blocks remaining indicate the structure of the roller conveyor and its positioning.

Figure 43 - Depiction of the base principle behind the choice of rollerways (courtesy of Ficep S.p.A.)

All sub-assemblies of the handling system (loading-tables, unloading-tables, IN-roller conveyors, OUT-roller conveyors) are in turn composed of modules that automatically adapt their characteristics to meet the specifications inserted and avoid conflicts.

The prices indicated below each table indicate in the first row the price of the standard solution and the second row the price of the customized solution that optimizes the functionality of the system with respect to customer demands.
4.7 Cost estimation

As a corollary project, the configurator has also been linked to the price lists of the supplier, in order to provide an accurate estimate of the costs of the various modules of the handling system (distinguishing between price for standard features and price with customizations) in a very short time and completely automatically.

This has made it possible to quickly generate the data on the price trend of the modules with varying linear weight and length of the profile to be processed, useful indications for the generation of a Ficep list with a modular composition of costs.

As can be seen by the chart the prices are not linear, as they depend mostly on the number of arms of the loading / unloading tables (which is not a linear function as follows from equations 3 and 4) but can be linearized maintaining a sufficient accuracy (dotted lines in the graph).

Passing to non-standard linear weights of the profile, the function of delta cost can be calculated as the difference of the two linearized cost functions.

The red area in the graph represents the delta cost between the price of the roller conveyors on the inlet side for standard linear weights (<500 kg/m) and a linear weight of 1085 kg/m as a function of the length of the profile.
5 Discussion and conclusions

5.1 Discussion of method

The methods used have been chosen as the study progressed, identifying the closest and best adaptable to the needs of the project from time to time. Thanks to the guidance received both by the company and the partner the choice has always resulted to be appropriate and suitable to structure the research towards the goal. The method used, represents itself the most general finding of this work, as can be applied to the optimization in modular and standardized key of any kind of product.

5.1.1 Literature research

In interpretivists approaches this method is crucial for the definition of the research plan, by gathering information from previous works on the topic. In this case as well it has satisfied its function and provided a wide knowledge and comprehension on the subject even before moving to the company.

5.1.2 Market analysis

The understanding of current and forecast of the future trends of the market gives indication of the direction in which to work to get advance over the competitors. Here the study of the options nowadays available showed a gap in the market for modular and reconfigurable handling systems.

5.1.3 Brainstorming

This activity, as expected, generated a considerable amount of data regarding customer needs and interests, that have then been set as goals to satisfy at end of the project. The only downside, considering the expense of time and resource for the number of people involved, could be the time restriction to a single session and for a limited number of hours, but fortunately the results obtained were sufficient by themselves and did not require further time or sessions.

5.1.4 Case studies

This method has often proved to be the most convenient source of information as characterized by a high reliability (verified cases). For this reason, it has been used in an interactive way also in the testing phase of the configurator to check the consistency of the results.

5.1.5 Interviews

The advantage of interviews is of course the possibility to leave the train of thought to drive the exchange of information, going in deeper in the topic whenever needed. As for brainstorming the limit of this method is availability of the interlocutor and the expense of his time.

5.1.6 Functional decomposition

Functional decomposition resulted to be the most efficient way to find the hierarchical structure of the subfunction starting from the main function. The main difficulty lays in the articulation in words (verb + object) of actions implicitly taken for granted.
Discussion and conclusions

5.1.7 Function means tree analysis

This method was a pretty straightforward way to obtain a modular product structure by associating functions to physical modules, keeping a suitable level of detail.

5.1.8 Interface analysis

This aspect involved consultancy from other employees of the company working on the electronic aspects of the system to validate the proposed modular product architectures, guaranteeing the preservation of all their functions.

5.1.9 Linear optimization

Recognising the nature of the loading / unloading table disposition problem as a linear optimization problem represented a game changer in the development of the configurator, as the software already owned the solver tool to address this kind of problems. This built in tool is extremely useful in the resolution of linear combination problems, as it does not require extensive coding, even though it can only handle one objective function at a time and the definition of the constraints does not include a “different from” option.

5.2 Discussion of findings

The revision of the architecture of the machines in a modular key provides numerous advantages such as:

- less complex plant engineering and therefore greater ease of assembly (from Ficep’s side) and maintenance interventions in the event of a fault (from the customer side);
- ability to generate new models more quickly (and therefore greater flexibility and ability to adapt to the different needs of the market);
- optimization of spare parts warehouse management (from the customer’s side)

It is in fact estimated a reduction in assembly time in production of at least the 25% and in installation and line star-up times of at least 30%

Modular architecture as widely confirmed by the literature is a driver for the increase in the performance of the production system, especially from the point of view of the greater and more efficient reconfigurability, longer lifecycle of the plants thanks to reconfigurability and therefore less waste of resources for replacements, greater versatility of the systems and greater ability to adapt quickly to the changed production needs (in terms of volumes and products)

The intermediate milestones reached along the way basically built up onto each other, laying the base for the development of the final configurator and method.

The collection of customer specification and their following translation in technical specifications of the system were the starting point for the next step, in which the relationships between technical specifications and general characteristics of the roller conveyors and loading / unloading tables. This knowledge was implemented in a first version of configurator able to give answers only for standard profiles. The fact that in most cases customer are not interested in a single profile but rather on a whole range of profiles within certain dimensions was an indicator of the inadequacy of the first solution developed.

In order to adapt the structure and components of roller conveyors and loading / unloading tables it was obviously necessary to establish standard modules that made them up. Through functional decomposition and the subsequent function means tree
Discussion and conclusions

analysis the new modular architecture was obtained. At this point the arrangement and presence/absence of option have been standardized through product variants charts. The sum of all these results has made it possible to develop a configurator to ease the work of designing the whole handling system. The configurator offers advantages in terms of time and effort saving even though the results it generates have to be still evaluated and eventually corrected for special cases. The automation of the calculations showed the possibility of combining the configurator with cost estimation, this way reducing even the time spent for these calculations in the offer stage. At the state of the art, cost estimation is only possible after the layout has been defined (approx. Between 1 – 4 hours) and being done manually it takes about 20 minutes. With the configurator no CAD design of the layout is necessary for the planning of layout and cost estimation and it only takes less than one minute. The objective for further work is the integration of the output values of the configurator with an executable to automatically draw the 2D/3D layouts; the time expense would then depend mostly on the hardware characteristics of the computer that has to perform the job.

5.2.1 Evaluation of results

Below the considerations on the project of the two employees that will use the configurator before eventual sharing of filtered versions with the whole R&D department and sales.

Alberto Bossi – Ficep Product Manager

The purpose of the study was to make the most common possible the parts used and to define standard rules for the disposition of the elements. The configurator calculates itself both the structure and the layout of the handling system elements this way guaranteeing consistent solutions regardless of the designer. It checks that every element does not go over its structural resistance limit and at the same time offers all the possible compromises between costs and performance, for example adding/removing motors and loading / unloading tables translator arms according to the potentialities of each kind of table. As for the cost estimation, the process is currently carried out by hand after the layout, by the sum of the standard tables and roller conveyors. The current process is time and effort consuming while pretty accurate, with the configurator it won’t be necessary to draw the layout and then calculating the prices as a consequence. The downsides are the fact that the configurator has just been developed and still needs testing and adjustments before being shared with the rest of the company. Another problem is the management of requests too far from the standards and specific customizations unpredictable for the software.

Matteo Falcetti – layout designer

Being in charge of the maintenance of the configurator (e.g. update of pricelists) a positive aspect is the development in Microsoft Excel, a well-known and solid software. The use of charts in the development logic eases the comprehension of its inner working in case of later changes. The main problems are represent by the fact that it is still some sort of beta version and the fact that it has been developed using the ground theory from case studies of standard cases, results in not completely reliable results for requests that do not fall within normal cases (e.g. need to change the centre distances between translator arms of the loading/unloading tables to work around obstacles in the client’s plant).
5.2.2 Research questions and answers

RQ 1 How can customer requests be translated into technical specifications of the system in a standard way?

Starting from the description of the machining the customer has to perform, type of machine tools, profile dimensions and weights are defined. The process of market analysis of the customer needs can be summarized as follows:

1. Collection of the description of the final product they want to produce
   → type and dimensions of the profile under machining
2. Definition of the type of mechanical machining to be performed
   → choice of the machine tools from Ficep’s catalogue
3. Notation of the morphology of the location the system will be settled into
   → overall dimensions of the system and position of eventual obstacles to be worked around

RQ 2 What are the relationships between technical specifications and physical characteristics of the constitutive elements of the handling system?

The physical basic structure of the elements is defined according to the static and dynamic structural strength required for the translation of the profiles belonging to the range defined in the technical specifics. Roller conveyors’ support structure and diameter dimension are chosen through confrontation of the operating conditions defined by customer specifics and range between the extreme cases in which each variant can be employed. Loading / unloading tables size is selected on the base of their transferable weight, while the number of translator arms is adjusted to cover the length of the beam minimizing the overhang and to keep the spacing between them inferior to the size of shortest beam moved.

RQ 3 How can a new architecture of the products in modular configuration be derived still guaranteeing the fulfilment of each function?

The technical specifications deriving from the customer requests are articulated as functions, following a bottom down approach in which the main function gets gradually broken down into subfunctions through the process of functional decomposition. The mapping between functions and physical modules is done using the function means tree approach, in which the hierarchical decomposition of functions is associated to the product components and subassemblies that fulfil every function. The modules are then identified on a functional base. The last check for the proposed modular architecture regards the interfaces between modules that have to be compatible and standardised to allow interchangeability as well as the transmission of material and power flows.

RQ 4 What are the rules for the configuration of the handling system and its components?

For the configuration of the handling system two main tasks must be performed:

1. Choice of the elements and their structure
2. Design of the layout

For the choice of the elements in the handling system and their structure the first rule is to eliminate from the possibilities the elements whose working conditions ranges do not include the ones required by the costumer. This distinction between suitable and unsuitable elements is grounded mostly on the sizes of pieces transferable and
Discussion and conclusions

Adequacy of both static and dynamic mechanical strength of the components with respect to the loads to move. The components are chosen among the available variants so that their operating conditions will never exceed their working range. Optional components must be selected to suit the functions to perform and not interfere with the other machines of the plant. Once the components and their inner structures are defined according to the specifics, they have to be arranged to allow transportation of material in the plant. The definition of the layout has to keep in mind constraints related to the shape and dimensions of the final location in addition to the length of the beams to be moved. This rules for layout can in general be summed up as:

- All centre to centre distances of the loading/unloading table's translator arms have be inferior to the length of the shortest beams transferable
- The dimensions of centre distances between translator arms have to grow moving away from the machine tool
- The sum of the centre distances has to be shorter than the longest profiles movable
- The overhang must be minimized
- Aligning all the beams on the machine side for unload, the centre of gravity must always remain centred between two translator arms and the moment generated by the overhanging portion of the profile must be balanced by the translator arms' support
- No overlapping of any kind is allowed between roller conveyors and tables
- All roller conveyors must fit in the centre distance between table's translator arms
- The distance between one roller conveyor element and the following must have a constant value

All these rules for choice and layout have been implemented in a configurator able to perform these tasks automatically taking as inputs the technical specifications derived from customer requests.

RQ 5 What model allows a reasonable estimation of the costs of the system?

The linearization of the function of the cost of each product family for standard weight with respect to the length of the profile, plus the functions of delta costs deriving from personalization.

To estimate the costs of the handling system the prices of the product families that make it up have to be evaluated separately. Being all this costs dependent on the length of the profile, on the weight and on the number of translator arms their trend has a stepped shape, so in order to make it a function it has been approximated with his linearization this way eliminating the dependence from the number of translator arms. The additional costs for customizations have been derived as the functions of the delta between the standard case and the customized one, with respect to the length.
5.3 Conclusions

All the research questions have been addressed and fulfilled in order, as the resolution of each one of them constituted the starting point for the following. All the intermediate outcomes have then been implemented in the creation of the configurator, showing that it is possible to rethink the handling system architecture as the assembly of standard modules, optimizing the compromise between costs and performance. The configurator has been tested and verified by comparison to past known cases and despite not being still always able to supply the desired outputs, it has proven to be reliable and accurate on the normal cases which the project was aimed for.

5.3.1 Possible future developments

The developed configurator was conceived with a view to being then implemented with an executable in order to be able to automatically generate the 3D layouts of the Ficep standard system configurations by exploiting the data calculated in this way.

Figure 46 - Example of 3D line layout automatically generated using dummy models of machines
6 References


Descartes, R. (1619-1630). *Regulae ad directionem ingenii*.


