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Hybrid kitting systems: an analysis of design variables and contextual factors affecting performance.

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Abstract

Nowadays collaborations between humans and robots in industrial realities is growing, in relation to benefits and advantages in using new technologies to standardize and optimize processes and operations. Moreover, robots can not only replace the human operators, but also support them in their tasks execution aiming to reduce fatigue and ergonomic problems. Robots collaboration can be used in many contexts as production, assembly, transportation, etc. Parts feeding activities are related to the supplying of materials needed for the production and the assembly systems; depending by the material characteristics (as weight, dimensions, utilization, cost, etc.), there are different part feeding policies that can be applied to optimise these activities, as pallet to workstation, trolley to workstation or kit to assembly line. More specifically, "kit to assembly line" feeding system also known as "kitting" is often preferred to "pallet to work station" feeding system also known as "line stocking" for small components that have a large number of variants and a low usage rate.

In this context this thesis aims to analyse a hybrid system for kit preparation i.e., a system where picking operators and collaborative robots collaborate to prepare kits to be delivered to the assembly line. With kitting, assembly processes are supplied with kits, collections of components needed to assemble a specific end product "EP" which is sequenced on the assembly line.

In relation to "line stocking" material feeding the use of kitting can result in benefits by improving space utilization in assembly lines, reducing the time spent searching for components by assembly operators and assuring the correct components being assembled.

The use of collaborative robots to support kits preparation has received some attention by researchers, but literature is lacking with respect to benefits that collaborative robots bring to the kits preparation system affecting its performance. To complement this limited knowledge, three research questions were formulated focused on respectively: the influence of the design variables on time-efficiency of the hybrid kitting system, the categorization of components based on their characteristics and the influence of the contextual factors on time-efficiency of the hybrid kitting system.

With reference to each research question, experiments have been developed at the same time as an analysis of the previous literature. In particular, the answer of the research question 1 has provide only an analysis of the previous literature, while for

the research question 2 and 3, appropriate experiments have been developed, respectively, with the aim of obtaining a classification of components based on their physical characteristics and to study the influence of contextual factors on time-efficiency of the hybrid kitting system.

First results show the five design variables on which attention must be focused in order to be time-efficient: high picking density, larger batch size, adequate picking information system, moving kit cart, balance between manual and robotic work. Second result provide a model of categorization of components based on their characteristic, supported by the experimental evidences. Third result shows that the context variables that most influence time-efficiency are: component size and easiness of grasping.

This thesis contributes to theory and to practice about the potential of collaborative robots in the hybrid kits preparation. Further research should explore how collaborative robots could support the kits preparation in other settings, for example in warehouse order picking. Furthermore, aside from time-efficiency, future research should consider how collaborative robot applications affect other performance of kits preparation such as flexibility, quality, ergonomics and cost.

Acknowledgements

I would here like to express my gratitude to the people and organisations who have contributed to my research.

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I would like to thank my mum and my dad for having supported and tolerated me during all these years and for having, with their sacrifices, the possibility of being professionally and humanely fulfilled.

Finally, I couldn't forget to thank all my friends for taking me on this adventure, celebrating with me the achievements but above all encouraging me in difficult moments. Without you I would have never made it through to became who I am today.

Stefano Rossi

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1. Introduction

This thesis deals with materials supply to the assembly line in production system. Specifically, the focus is on the "hybrid kit preparation" carried out by collaborative robots and operators. This chapter is divided as follow: the first section gives an overview of different line feeding policies, while the second one presents the kitting policy for assembly lines. Finally, last part explains the purpose of this study, which is focused in 3 research questions, presented in section 1.3.

1.1 - Line feeding policies

In the Assembly to Order (ATO) and Make to Order (MTO) production systems, the request of customized goods is increasing more and more; to better response to the market demand, innovation in manufacturing and information technologies is required. It is becoming increasingly possible to assemble or make products specifically according to the requested of either end-customers or retailers. As a consequence of such customization, the design of the whole system must evaluate several elements: parts warehouse location, feeding policies and feeding systems (Battini *et al.*, 2009). It is important to select the optimal material handling system to carry the different components from the storages to the assembly lines. These policies allow a timely supply of all necessary items to work stations to complete the required tasks in the entire assembly cycle, in order to guarantee the best level of flexibility and efficiency of the whole assembly system. Generally, these policies are classified in three main groups: Pallet to Work Station, Trolley to Work Station and Kit to Assembly Line. More details about feeding policies are present in the section 2.1.

1.2 - Kitting in materials supply to assembly

During last years, the material feeding principle of kitting has received increasing attention as an alternative to continuous supply, also known as line stocking. It consists in preparing a "kit", a collection of components needed to assemble a specific end product "EP" which is sequenced on the assembly line (Bozer and McGinnis, 1992; Brynzér and Johansson, 1995). In relation to continuous supply - a parts feeding policy in which every different part type is supplied to the assembly line in an individual container holding multiple units of the same item - the use of kitting can result in benefits by reducing the space consumed at assembly stations, reducing material handling of the assemblers, supporting the assembly operations and providing potential for quality improvements (Hanson and Brolin, 2013). Therefore, kitting is often applied in the materials supply to mass-customized assembly, where it can facilitate the supply of a large variety of components. On the other hand, the kits preparation, is typically reported as labour intensive, and time-efficiency is the key for keeping running cost low (Hanson and Medbo, 2019).

The preconditions for order picking performed in kitting system differ from those traditional order picking system, mainly in the sense that information about the product is available in the form of product structure and that there is usually a production schedule to follow (Brynzér, 1995). The common reasons for introducing kitting in supply system are:

1) to improve space utilization in assembly lines by presenting materials in heterogeneous packaging (Limère *et al.*, 2012);
2) to improve assembly efficiency by reducing the time spent searching for components (Hanson and Brolin, 2013);
3) to facilitate the cognitive process of the assembler, thereby assuring the correct components being assembled (Medbo, 2003);

However, to realize those benefits, the kits preparation needs to operate at expected performance levels and to meet the requirements given by the assembly system. To reach this goal, choosing the design of processes for kits preparation by adjusting certain design variables is crucial, and it has to consider the context in which the design is deployed and the performance that it can yield.

Using kits preparation instead of materials supply methods for delivering packages with homogenous contents (containing a single component number) to assembly (for example, line stocking or continuous supply) introduces extra materials handling operations into the material flow (Limère *et al.*, 2012) that has received great criticism in discussions of kitting as an alternative materials supply method (Bozer and McGinnis, 1992). However, the additional materials handling work introduced by kitting, can be balanced by the efficiency gained in assembly from less walking and searching during component collection (Hanson and Finnsgård, 2014). As such, improving the time efficiency of materials preparation is central to improving overall production system efficiency when using kits preparation.

Traditionally the kits preparation is carried out by human operators. The manual kits preparation is subject to human errors that lead to errors in kits, which are deleterious and costly at assembly processes (Caputo *et al.*, 2017). Besides the human efficiency is not always constant during the working shift, introducing a considerable variability in the time needed for kits preparation. Recent research has shown that cobots - that is, collaborative robots that share workspaces with operators - can support time-efficient kits preparation by relieving operators of some of the tasks in kits preparation, while simultaneously supporting kit quality by removing the risk of human errors (Boudella *et al.*, 2018; Coelho *et al.*, 2018; Boudella *et al.*, 2016). Kits preparation supported by cobots has received less attention, and there is a lack of a standard procedure/framework to apply cobots in kits preparation. Moreover, the literature points out several challenges with respect to making use of collaborative robots to support kits preparation, including that robots must be capable of identifying the correct orientation of items to properly grasp them with suitable grippers (Martinez *et al.*, 2015), and that they need to display enough flexibility for dealing with variability in production settings (Kootbally *et al.*, 2018).

1.3 - Purpose

From the previous paragraph, it is clear that the use of collaborative robots brings various advantages in the kits preparation respect to the manual kitting. Furthermore, having a human-robot collaboration in kitting system could be an interesting alternative to achieve a good product customization by implementing flexible and highly reconfigurable production system, which can swiftly switch between different products (Boudella *et al.*, 2018; Coelho *et al.*, 2018). On the other hand, it is not straight forward how these cobots can help operators in the kits preparation and how hybrid kitting system - the collaborative kits preparation performed by operators and robots - can be designed in order to achieve the desired performance, defining the so-called design variables. Design variables are, for example, the size of the picking area, the picking information system and ending with the type of storage package. Moreover, in an industrial application, in addition to the design variables, chosen by the designer of the kitting area, there are other factors concerning the particular application context. These factors can vary depending on market demand, which determines the volume and the production mix, and they have an influence on the performance of the kitting system. Among these factors, the physical characteristics of the components, such as size and shape, play a fundamental role. For this reason, an appropriate classification of the components, according to these aspects is useful to understand their influence on the contextual factors.

By knowing the link between design variables, contextual factors and the time-efficiency performance of the kitting system, many managers and designers would have a guide on how to design and organize new kitting stations, taking into account needs and constraints. In this way it would be possible to develop a mathematical model that helps us to predict the cycle time needed for the preparation of a kit, which takes into consideration both design variables and contextual factors. Hereby, the purpose of this thesis is stated as follows: *To provide knowledge about how cobots collaborate with operators in kits preparation to assembly influencing performances*.

1.4 - Research questions

Three research questions have structured the research conducted for this thesis, largely to align the work with purpose presented in section 1.2. An argument of relevance accompanies each research question presented here in order to give the reader an overview of the relevance of each question. Further details concerning each research question are presented in the theoretical framework described in Chapter 2.

1.4.1 - Research question 1

One of the reasons for introducing the kitting system in the supply of material to the assembly line is to increase overall efficiency in the assembly of finished products. Since the introduction of kits preparation determines additional activities, in addition to the supply of components from the warehouse to the assembly line, the kitting activities must take as little time as possible and therefore have a high time-efficiency. The need that emerges is to understand how design variables relating to the preparation of kits influence the time-efficiency of the kitting system.

A similar analysis has recently been carried out, but only concerning the efficiency of the manual kits preparation, without considering the use of collaborative robots (Hanson and Medbo, 2019). The concept of design variables and performance are further described in the Chapter 2 and the result is presented in Section 4.1.

Research question 1:

How does the design variables influence the time-efficiency in hybrid kits preparation?

1.4.2 - Research question 2

Nowadays there is a huge demand for customized end products to meet the needs of consumers. To achieve this, it is necessary to use plenty of different components, differ in their physical characteristics. Therefore, it would be important to have a classification of the components, based on their characteristics, such as to be able to optimise the allocation of components between manual and robotic area in the hybrid kitting system.

Research question 2:
Which component characteristics affect components suitability for picking by robot and operator, respectively?

1.4.3 - Research question 3

Previous research studies how contextual factors influence the performance of the kitting system, concerning the manual work, without including the use of the robot in the kitting system (Hanson and Medbo, 2019). However, the use of collaborative robots as an assistance in the kits preparation process is definitely a trend topic. The performance of the hybrid kitting system is inevitably influenced by the factors of the industrial context in which one works.
The third research question is focused on the performance "Time-efficiency", which indicates the average time needed to kit a single component by an operator and a robot working in collaboration with each other. Furthermore, it could be interesting to develop a model thanks to which the cycle time needed for complete a kit can be estimated, taking also into consideration both the design variables and the contextual factors.

Research question 3:
How does the contextual factors influence the time-efficiency in hybrid kits preparation?

2. Theoretical framework and Background

This chapter presents the thesis's frame of reference and serves as the theoretical basis for the research. This is achieved by a review of literature that is relevant to the thesis purpose, as stated in section 1.3, to contribute to the knowledge about how collaborative robots collaborate with operators in kits preparation to assembly. This chapter explains the contributions from previous research that make up starting points for finding answers to the research questions addressed by this thesis.

This chapter is organised in 6 sections. Section 2.1 defines the term "kits preparation design". Section 2.2 presents the concept of design variables. Section 2.3 defines the kits preparation performance. Section 2.4 analyses the design variables content in this thesis. Section 2.5 defines the contextual factors and explains how the context is treated in this thesis. Finally, Section 2.6 shows the hybrid kitting system in detail.

2.1 - Line feeding policies

Bozer and McGinnis (1992) wrote the seminal paper about the problem of deliberately choosing between kitting and line stocking - a parts feeding policy in which every different part type is supplied to the assembly line in an individual container holding multiple units of the same item. They proposed a descriptive model which can be used as a tool to facilitate a quantitative comparison between various kitting plans. However, although the model serves as an evaluations tool, it does not help directly in designing an overall cost-effective materials supply system. Caputo and Pelagagge (2011) extended the formulation of the previous authors and propose using an ABC analysis as a basis for developing hybrid policies.

Battini *et al.*, 2009 consider three line feeding policies: Pallet to Work Station - Trolley to Work Station - Kit to Assembly Line. They simultaneously consider the centralization versus decentralization decision of component storage as well as the choice of the right feeding policy. The centralization problem is addressed through a search of a tradeoff between inventory and material handling costs. Then, based on a multi-factorial analysis involving parameters such as batch size, number of components, and distance between warehouse and assembly line, a single optimal feeding mode is chosen for the complete line.

In the "*Pallet to Work Station policy*" the required components are carried from the warehouse area to the different assembly lines using the item unit load, also called *pallet*.

As a specific production order creates a need for different components, which depends on the specific product order, all the required components are supplied carrying the entire unit load for each component, from the warehouse to the specific work station where the component is used. This is a typical situation in multi-model assembly lines of well standardized products. When the part is no longer needed on the assembly line, the unit load is brought back to its location inside the central warehouse, as shown in the Figure 1.

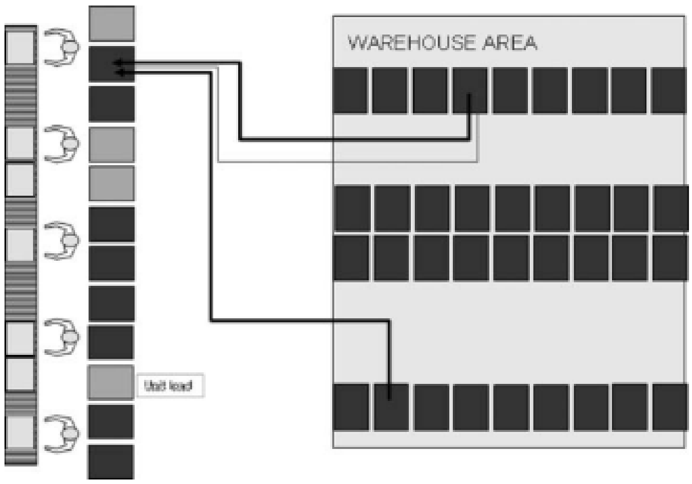


Fig. 1 - Feeding system: "Pallet to Work Station"

This feed policy is ideal when the delivered components are used in the same workstation during a specific period, since it does not require carrying back the item unit load, during the given period. This strategy is useful when the item unit load is used up completely by the work station, both with low and high frequency, eliminating the necessary for return trips to the warehouse. On the other hand, several problems arise with the transportation of entire unit loads, in fact, all the unpacking activities need to be executed by the assembly operators, which involves extra movements and extra tasks performed by the workers, reducing the efficiency both of the single operator and of the whole assembly system. Moreover, the inverse flows from the line to the warehouse, the space occupied near the line and the total transportation costs increase because the entire pallet and not only the exact quantity required from the different work station is moved back and forth.

In the "*Trolley to Work Station policy*" the components for each workstation are compiled into lists. These lists are used by the warehouse worker to collect the components necessary to complete each activity from the storage area and load all the components into a trolley that will be assigned to the specific assembly line station that requested the material. After the trolley is loaded in the warehouse, it is moved to the assigned work station. In this type of system, the assembly workers handle only the components used during their assembly tasks (Figure 2).

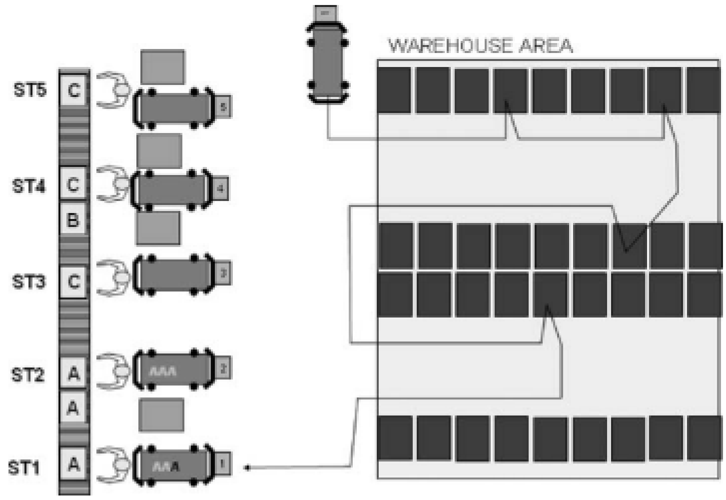


Fig. 2 - Feeding system: "Trolley to Work Station"

In comparison with the previous policy, this feeding system allow to reduce the number of travels from warehouse to the assembly lines; it reduces the components storage space near the work station and makes the components readily available (unpacked) to the assembly workers, reducing the production time and increasing the efficiency of the entire line. This strategy is useful when each component is not used frequently and when its size is limited, because the trolley carries only the right quantity of components for a given number of items, as requested by a specific work station. In addition, the Trolley to Work Station policy is convenient when the quantity of different components for each single trolley is not high, and the distance between the warehouse and the work station is limited. In conclusion, this approach is interesting only when the components present specific characteristics, such as small size and low frequency.

The "*Kit to Assembly Line*" strategy consists in creating a kit of components for every end-products, assembled on the assembly line, each kit contains the product's main components and each kit is destine to the production of one item. The production scheduling determines the number of kits needed from the warehouse during a specific period of time. So in the warehouse one kit is prepared for each finished product, and then each kit is sent to the assembly line, where it is assigned to a specific work station according to the specific end-product and it passes through the entire line, from the first station to the last, as shown in the Figure 3.

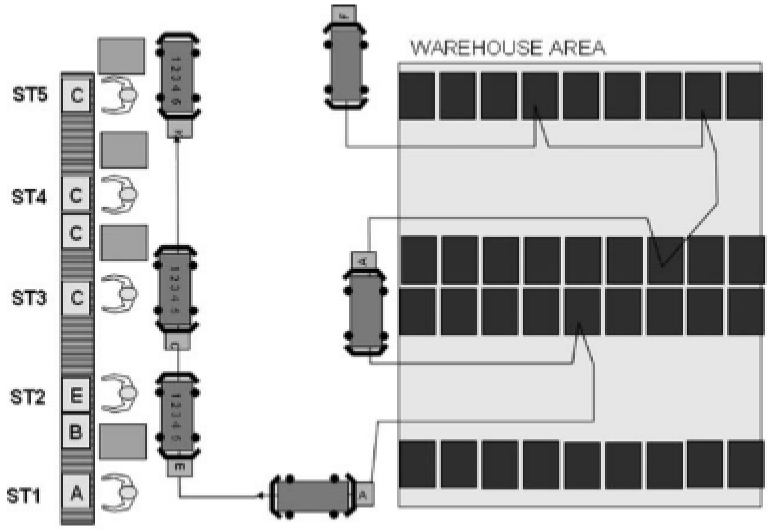


Fig. 3 - Feeding system: "Kit to Assembly Line"

The Kit to Assembly Line strategy can be used in different assembly system, like the classical sequential line or the assembly system with parallel stations, and it presents similar advantages and disadvantages of the Trolley to Work Station Policy. The only difference between these two strategies is the number of prepared kit or trolley. In fact, in the Trolley to Work Station policy, the number of trolleys is a function of the production batch size, number of stations, number of common parts in the assembly family, size of the trolley and size of the components. In the Kit to Assembly Line policy, the number of prepared kits is exactly equal to the number of end-products for each work station and it is not a function of either variables of the production system.

This research showed that the batch size is the most critical factor in choosing the right feeding policy. In fact, for smaller batch size the Kit to Assembly Line policy, is perfectly acceptable and convenient. As the batch size increases, the distance between warehouse and assembly line becomes a factor to consider: when the distance is low and the batch size is medium-high, the Pallet to Work Station policy will be the most convenient. On the other hand, when the distance between warehouse and assembly line is high, the Trolley to Work Station policy is more suitable, depending on the batch size. In the Pallet to Work Station policy, reducing the number of components for each end-product, with a standardization policy during the design of the end-product, has relevant effects on the total time necessary to feed the assembly line. In addition, keeping the warehouse closer to the assembly line, significantly reduces the total production time.

Sali *et al.* (2016) present an empirical assessment of the performances of line stocking versus kitting versus sequencing. They proposed an optimization model that assigns each individual component to the most efficient line feeding mode among the three different alternatives.

Although some of the previous research indicates a belief in the usefulness of hybrid feeding policies, a theoretical foundation for the selection of the delivery strategy for individual parts is not put forward yet. Both Hua and Johnson (2010) and Faccio *et al.* (2013) recognize that research should identify and analyse the influencing factors in the part feeding decision problem. Limère *et al.* (2012) made a first effort in this direction. They proposed a mathematical cost model for the assignment of all individual parts to one of both materials supply methods in an overall cost-effective way. This model performs well, except that it assumes constant operator walking distances at the line. However, previous research has shown that smaller packages at the line (e.g. kits) reduce operator walking distances (Wänström and Medbo, 2009; Neumann and Medbo, 2010; Finnsgård *et al.*, 2011; Hanson and Medbo, 2012). The purpose of this research is therefore to extend the research to take into account variable walking distances.

2.2 - Definition of “kit preparation design”

An important aspect of this thesis is *kit preparation design*, a term widely used in literature, consisting of three words, both having a close connection with the purpose of this thesis. In the following sections both meanings will be explained and analysed.

***Kit* -** defined as “A collection of components needed to assemble a specific end product “EP” which is sequenced on the assembly line” (Bozer and McGinnis, 1992).

Preparation - defined as “The action or process of preparing or being prepared for use or consideration” (Oxford English dictionary). The word “process” is here defined as “A series of actions or steps taken in order to achieve a particular end” (Oxford English dictionary).

Design - defined as “A specification of an object, manifested by some agent, intended to accomplish goals, in a particular environment, using a set of primitive components, satisfying a set of requirements, subject to some constraints” (Ralph and Wand, 2009).

2.3 - Design framework of hybrid kitting system

The definition from (Ralph and Wand, 2009) is used in this section to derive design framework used in this thesis. The definition of design is reproduced in the Figure 4.

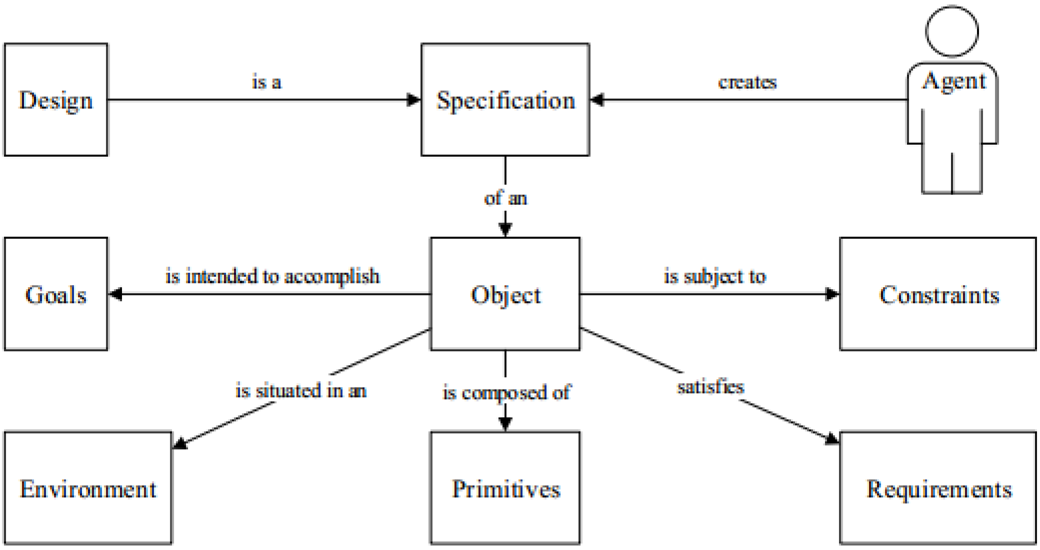


Fig. 4 - Design framework (Ralph and Wand, 2009)

The design is intended to accomplish performance *goals* and to fulfil the *requirements* stemming from the production system. The design is composed by the design *primitives*, which is "the set of elements from which the design object may be composed". The design *object* is the thing being designed. A *specification* is a detailed description of a design object's structural properties. Clearly, the design process occurs within some *environment*. The requirements suggest the properties or behaviors that object have to possessed. Furthermore, all design must involve *constraints*. There are two criteria for an element to be part of the design in this thesis: that the element has an influence on the kits preparation performance and that the element is subject to choose for the designer. The influence can either be direct or indirect, meaning that the element either directly influences the kits preparation performance, or it influences another element which in turn influences the kits preparation performance.

Those elements of the kits preparation process that do not influence the kits preparation performance, nor are subject to the choice for the process designer, are considered as ***contextual background elements*** and reside outside the scope of the thesis. Those elements that neither have a direct nor indirect influence on kits preparation performance, but are subject to the choice for the designer, are classified ***design background elements***. Those elements of materials preparation that have either a direct or indirect influence on materials preparation performance, but are not subject to the choice for the designer, are part of the kits preparation context and classified as ***contextual factors***. Those elements of kits preparation that either directly or indirectly influences the materials preparation performance, and are subject to the choice for the designer, are part of the kits preparation design and are classified as ***design variables*** in the thesis.

Figure 5 shown the contextual factors and design variables that are considered in the research are those linked to the performance objectives considered in this thesis.

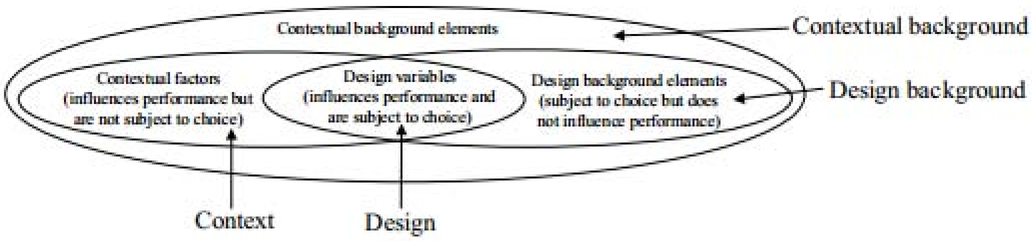


Fig. 5 - The elements of kits preparation, illustrates how the terms design and context are treated in this thesis.

2.3.1 - The concept of "design variables"

A variable (noun) is "an element, feature, or factor that is liable to vary or to change" (Oxford English dictionary, 2016). A kits preparation design variable is an element of the kits preparation design that either directly or indirectly influences the kits preparation performance, and is subject to choose for the kits preparation designer. To comprehend this definition, it is necessary to consider both that the requirements "has significance for the kits preparation performance" and "can be changed by the process designer".

For an element of kits preparation to have significance for the kits preparation performance, an alteration of the element must yield a change in the kits preparation performance. If the alteration of an element does not yield a change in performance, the element is not a design variable, neither is it a contextual factor. If the alteration of an element yields a change in performance, but is outside the circle of influence for the designer, the element is part of the kits preparation context.

2.4 - Kit preparation performance

This section presents a description of the kit preparation performance used in this thesis relative to the kitting area. In particular, this section will focus on the analysis of a single performance parameter: time efficiency. Then, a definition is given and the method by which this performance parameter can be measured.

2.4.1 - Performance framework

Performance measurement is a topic which is often discussed but rarely defined. Literally it is the process of quantifying action, where measurement is the process of quantification and action leads to performance. According to the marketing perspective, organizations achieve their goals, that is they perform, by satisfying their customers with greater efficiency and effectiveness than their competitors. The terms efficiency and effectiveness are used precisely in this context. Effectiveness refers to the extent to which customer's requirements are met, while efficiency is a measure of how economically the firm's resources are utilized when providing a given level of customer satisfaction. In terms of effectiveness, achieving a higher level of product reliability might lead to greater customer satisfaction. In terms of efficiency, it might reduce the costs incurred by the business through decreased field failure and warranty claims (Neely, 1995).

Compared with continuous supply, kitting has been reported to be associated with a number of potential advantages, such as space efficient parts presentation (Bozer and McGinnis, 1992; Medbo, 2003; Hua and Johnson 2010), improved assembly quality (Sellers and Nof, 1989; Johansson, 1991; Bozer and McGinnis, 1992), shorter learning times (Johansson, 1991), a more holistic understanding of the assembly work (Medbo, 1999) and less time spent by the assembler fetching parts (Johansson, 1991; Hua and Johnson, 2010).

Kitting is also associated with certain drawbacks. Most evident is the fact that the kits need to be prepared in advance, something that requires space and additional handling (Sellers and Nof 1986; Bozer and McGinnis, 1992; Hua and Johnson, 2010).

2.4.2 - Definition and measurement of the "time-efficiency"

The time-efficiency is defined as the ability to perform a task with minimal effort in terms of time (Oxford English Dictionary). In literature, time is considered a competitive advantage (Neely *et al.*, 1995) and to be equivalent to money.

Time efficiency should be assessed from the time spent on completing a specified content of work. In particular, considering the kitting environment, the "time-efficiency" could be defined as the time that occurred for complete a kit of components, picked from a kit container in the storage and placed into a kit package, by operator and robot.

2.5 - Kit preparation design variables

In this section, the design variables that define the kitting system are described.

2.5.1 - Kitting system design

In literature some methods for the evaluation of kitting system performance and derives six design factors of kitting system was studied (Brynzér, 1995). These design factors are: the layout, the picking information, the equipment selection, the storage policy, the batching policy and the picking policy.

Regarding the layout design factor, as shown in Figure 3, identifies the location of the kitting area in relation to the assembly line, the width and length of aisles and the location of shared equipment and areas. Concerning the picking information design factor, the picking information media and the structure of the picking information are considered important. As regards equipment selection, the two main considerations identified are the storage equipment and the picking package. The storage policy is concerned with the storage assignment policy, i.e. the logic behind the location of individual items in the storage. The batching policy refers to number of orders that are managed during a single picking tour. The picking policy is defined identically to the definition by (Goetschalckx, Ashayeri, 1989) and is in the kitting system concerned with the sequence in which picking locations are visited during a single tour, and whether the picking package passes through zones and, hence, is completed by different operators. As only single operator materials preparation is focused in the thesis, only the sequence with which the singular order is completed is within the scope.

The framework for kitting system design in relation to picking efficiency is shown in the Figure 6.

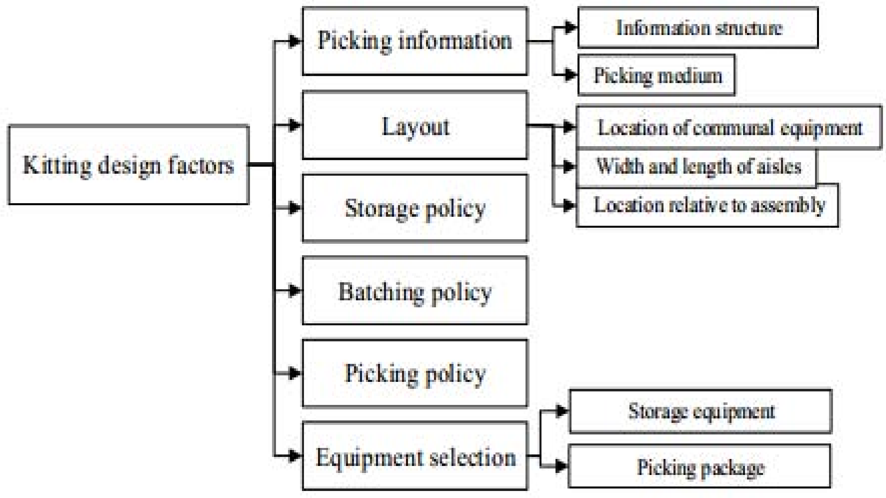


Fig. 6 - The design factors for kitting system (Brynzér, 1995)

2.5.2 - Design variables framework used in this thesis

In the following sub-section, each design variable is treated in terms of the values the variables might assume and the influence of the variables on kits preparation performance, as identified in previous literature. An illustrative diagram of the design variables used is shown in Figure 7.

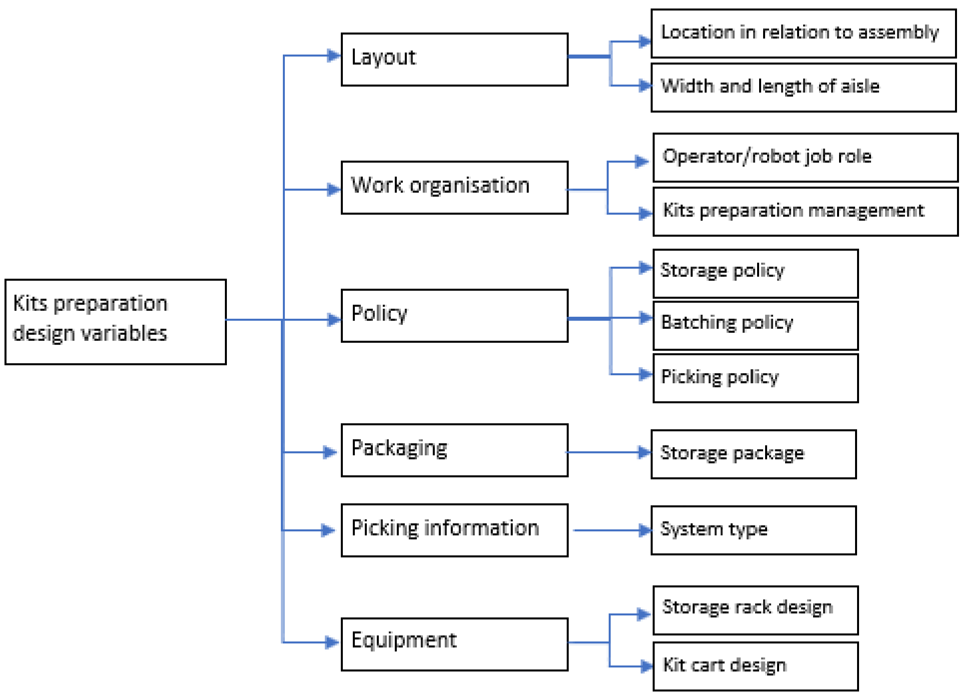


Fig. 7 - Design variables analysed in this thesis.

2.5.3 - Layout

Layout design is concerned with the location of the kit preparation area in relation to assembly, the position of shared resources at the preparation area and the length and width of the preparation shelves and the storage aisles (Brynzér, 1995).

The location of the preparation area in relation to assembly is a high level decision concerning the materials preparation design (Brynzér and Johansson, 1995) and is often part of the larger decision of whether to use a centralised policy, where multiple kits preparation processes are kept together in the same area, and a decentralised policy, where materials preparation is located close to assembly.

The location of the preparation area influences the options for the operator job role, where a location closer to assembly enables the assembly operator to conduct materials preparation, either individually or for the team. Further, a location closer to assembly enables balancing of operations between the materials preparation area and the assembly, which can reduce balancing losses in both assembly and materials preparation (Brynzér and Johansson, 1995). However, reduced balancing losses might also be achieved with a centralised policy, where work content instead can be balanced between kits preparation processes in the same department (Hanson *et al.,* 2011). A location farther from assembly tends to improve the flexibility of the kitting process, in terms of a higher availability of floor space that allows for extending the storage racks (Hanson *et al.*, 2011). On this note, a location farther from assembly could also improve the opportunities for designing the process more freely, thus facilitating the design of more a more time efficient kits assembly process.

The layout of the preparation area sets the movement pattern of the operator or robot in the preparation process, but also relates to several other design variables. (Grosse and Glock, 2013) investigates the influence of storage assignment policy on the time efficiency in U-shaped order picking areas and finds that the locations of the part numbers and the location of the picking package can influence time efficiency to a great extent. The position of shared resources in the preparation process concerns both the distances between key resources and the organisation of key resources, i.e. where the resources are located relative to one another. In regards to time efficiency, the location of resources as for example the printer and the discarding point for empty packages, will impact the movement pattern in the preparation area during the picking tour (Brynzér, 1995).

In summary, the location of the preparation area has partly a direct effect on the quality, flexibility and time efficiency of the materials preparation, and partly sets the preconditions for other design variables in terms of enabling or disabling certain design variable values.

2.5.4 - Work organisation

The kits preparation work organisation is concerned with the work tasks of both the operator and the robot who conduct the kits preparation, as well as the manner in which the management of the kits preparation are organised. These three aspects are here denoted as the operator job role, robot job role and the kits preparation management. The options available for the operator job role depends to a large extent on the localization of the kits preparation area (Brynzér and Johansson, 1995). It is generally considered that a job role where materials picking is combined with assembly work improves the picking accuracy due to that the operator knows the product structure and performing the kits preparation for own use (Brynzér and Johansson, 1995). Previous studies have considered robots supporting kits preparation by picking components from the storage (Boudella *et al.*, 2018), (Coelho *et al.*, 2018). Moreover, an important contribution to understand how a collaborative robot can support kit preparations by sorting components into a batch of kits has been given by (Fager, 2019). In both cases in which robots were involved into a kits preparation, there was an influence for the benefit of kit quality, as it removes risks of human errors when sorting components among kits and also a positive influence of time-efficiency, slightly reducing the time needed for the kits preparation.
Further, depending on how the kits preparation management is organised, aspects such as the conditions for continuous improvement (Hanson *et al.*, 2011) as well as the communication channel and the risk of interruptions (Brynzér and Johansson, 1995) could be impacted. Beyond this, literature appears scarce in regards to the influence of the management function on the kits preparation process performance.

2.5.5 - Policy

Policy in the design is concerned with the rules for determining the storage location for components, the number of kits treated during the same picking tour, and the sequence in which components are retrieved from the storage. These aspects are here treated as the **storage policy**, the **batching policy** and the **picking policy**, respectively.

The **storage policy** is concerned with the location of components within the storage (Park, 2012), both in the horizontal plane, vertically (shelf level), and in relation to the storage location of other components. According to (Park, 2012), there are three different types of storage policies available to warehouses: the random, the dedicated and the class-based storage policies. The random storage policy involves assigning a component number to a storage location without consideration to neither the activity nor the turnover for the component number, where the common heuristic rule is to store each new component number at the closest open location. The dedicated storage policy on the other hand use a fixed location for each component number, where a common heuristic is to organise the component numbers according to frequency, so that the component number with the highest frequency is located closest to depot. The class-based storage policy is an intermediate of the random and the dedicated storage policies, where the storage is partitioned in classes, where each class for example represent a frequency range, and the component numbers are stored randomly within each class. In contrast to the random, the dedicated and the class-based storage policies that consider the demand for a component number to be independent of the demand of other component numbers, (Brynzér, 1995) explain the correlated storage policy to consider the correlation in demand between component numbers, where component numbers that frequently are requested together should be stored together. In kitting processes, these correlations can be determined from the product structure (Brynzér, 1995).

In kits preparation, there are somewhat different preconditions from the more general warehousing context, due to the existence of a product structure and the dependence on the assembly schedule, which create a dependent demand among components (Brynzér, 1995). Thus, the components managed in the materials preparation process can be considered as more constant, in terms of the same component number being managed in the process over a longer time, than in the traditional order picking context of distribution centres. This implies that the storage assignment policy is dedicated at a given point in time. The differentiation as described by (Park, 2012) is rather concerned with where new component numbers should be located once they arrive to the process, and with how the location of component number should change upon changes in the demand characteristics.

The **batching policy** is the number of orders that are handled during a single picking tour (Brynzér and Johansson, 1995). The reason why batching policy has received significant attention in order picking is due its effect on time-efficiency, where it enables components for multiple order to be picked at once (Hanson et al, 2012). However, some literature points at that batching of orders might be associated with an increased amount of sorting and administration in kits assembly operations (Brynzér and Johansson, 1995). In order picking, batching is utilized in order to reduce the travel distance per completed order (De Koster *et al.*, 2007).

The **picking policy** is concerned with the sequence in which components are picked for a single order. This has implication for the movement across the picking area, where picking from alternate sides of the aisle can be contrasted with picking from one side at the time (Brynzér and Johansson, 1995).
By introducing picking zones into the storage, the picking sequence is affected. An order is divided between that zones and often the components are picked simultaneously, which makes a short lead-time in the storage possible.

2.5.6 - Packaging

The packaging used in the materials preparation is in this thesis concerned with the storage packaging type used in the material storage and the kitting package to which components are picked. The type of storage packaging that can be used is dependent on the component characteristics (Petersen, 1999).
The design of the picking package is very much dependent on the batching policy used, as well as the requirements posed by assembly, which is another set of contextual conditions. (Brynzér, 1995) identifies significant efficiency potentials from the design of the kitting package, but also remarks that the design options of the kitting package are a large extent dependent on the requirements on the materials preparation from the assembly, in terms of whether the kitting package uses a structured or unstructured design. A structured design of the kitting package could also improve the picking accuracy, as each component type then has a specific position and a missing or erroneous component is more easily detected.

2.5.7 - Equipment

The materials handling equipment design variable is concerned with the equipment types and the design of the storage, categorized as the aspects support equipment and the storage equipment.

Support equipment concerns the design of lifting devices, the design of trash bins and return trays for empty packaging that may be necessary to use due to contextual factors, as the component characteristics and the type of storage packaging used (Hales and Andersson, 2002).

2.5.8 - Picking information

The picking information concerns the information which communicates to the picker what is to be picked, where picked items should be placed. The aspects concerned with the picking information include the picking information system type and the information structure.

(Brynzér and Johansson, 1995) identifies several issues with how picking information is conveyed to the picking operator, in addition to how the systems used in industry are designed. Inappropriate design of picking information system impacts picking accuracy negatively, which creates disturbances in the storage and the production processes (Brynzér and Johansson, 1995). As explained by (Park, 2012), the use of automatic presentation of information is increasing, where the developmental direction is towards hands-free and paperless system. The primary advantage of using such system is the facilitated search and extraction process for items from storage and the reduction of picking errors (Park, 2012).

2.6 - The kitting context

In addition to design variables, context factors play an important role, which depend on the type of application being analysed, but at the same time influence the performance of kits preparation. The context is outside of what contributes to the definition of the kits preparation design, but includes those aspects that have an influence on the performance. This influence can be withered direct, in terms of directly contributing to the performance, or indirect, in terms of influencing the link between some other design variable and the performance. This type of factors is in this thesis denoted as **context factors**.

This section focuses on two contextual factors, resulting by the previous literature: component characteristics and the number of components per SKU. The SKU “Stock Keeping Unit” is defined as a number or set of numbers given to a product to show which particular one it is (Cambridge Dictionary).

- **Component characteristics**

The component characteristics are concerned with the size and shape of components. These factors were considered, as they found considerable influence in the man-hour efficiency, recently analysed in the literature (Hanson and Medbo, 2019). The term "shape" is used to analyse the shape characteristics of the component, linked to the easiness with which you can grasp that component.

- **Number of components per SKU**

The number of components per SKU is linked to the possibility to grasping a number of components of the same SKU at a time implying less time spent to pick components from the storage racks (Boudella *et al.*, 2018). The number of components the operator picks simultaneously for *SKU i*, is given by the minimum between the number of components of *SKU i* needed during a cycle and the maximum number of items that the operator can pick simultaneously. The maximum number of items that the operator can pick simultaneously depends in turn on the component size.

2.7 - Hybrid kitting system

This section describes the hybrid kitting system to which all the considerations regarding this thesis are related. The hybrid kitting system shown in Figure 8 is used as a reference to give an idea of a possible configuration in which the robot and the operator can collaborate in the preparation of the kits. Surely there are other configurations in which the robot and the operator can collaborate, for example, another configuration (Fager, 2019) could be the one in which the operator performs only one picking of the components from the shelves and then the collaborative robot, helped by a vision system, sorts the components into the different kit packages.

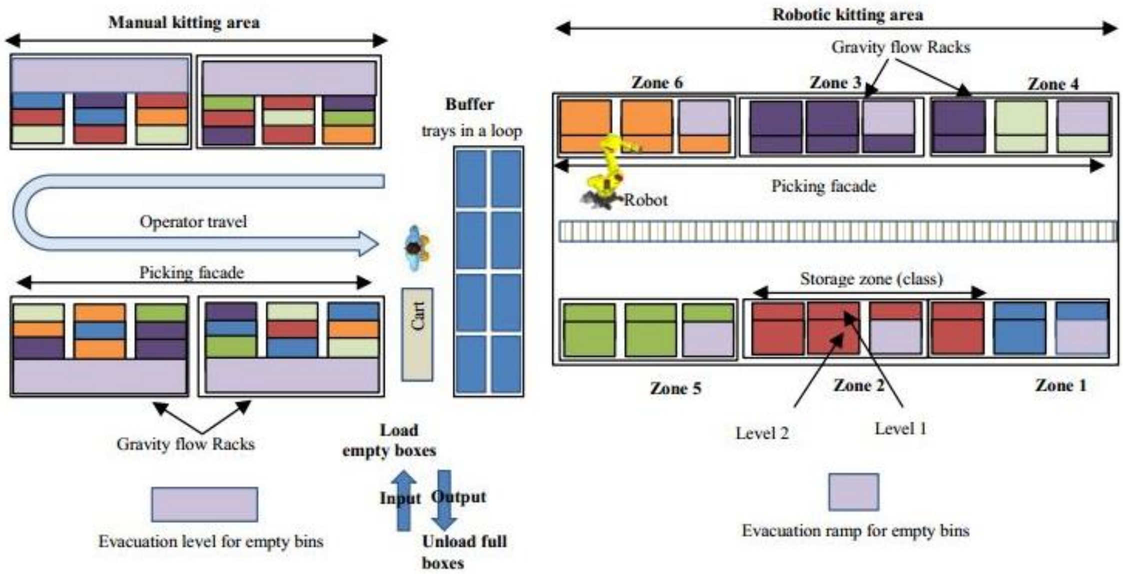


Fig. 8 - Hybrid kitting system shown in (Boudella et al., 2018)

In the (Boudella *et al.*, 2018) model, as can be seen in Figure 8, the manual kitting area is separated from the robotic kitting area. This representation shows the gravity flow racks on which the storage containers are placed, each containing a specific SKU "Stock Keeping Unit".

As a first step of the kitting process, robot picks components from storage packages located on a 2-level racks and place them on a moving conveyor that drop components within large trays located at the output of the robotic kitting area. This part of the robotic system acts as a buffer that we assume to be large enough to decouple the activity of the robot and the operator. Each tray receives components associated with one kitting packages. This is made possible because in that model they consider that SKUs are stored following a class-based strategy and inside each class, following a dedicated storage strategy. In their case, SKUs would follow a particular order, for example, from the heaviest components to more fragile one to prevent components from some damage. In addition to picking components, the robot has to remove empty bins.

As a second step, the operator retrieves components from the specific trays and placed them in the destination kit packages and complete the packages picking components from a 3-levels racks located in his aisle. To carry out the picking operation, the operator is assisted by a "Pick-by-light" system, which through a light indicator above each container kit, indicates to the operator the position from which he will have to pick the components. The quantity to be collected, assigned by production schedule, will be indicated by a light screen, positioned above each rack. While the operator works on picking components in his area, the robot simultaneously prepares the next kit in the preparation sequence.

Fig. 9 - An example of moving kit cart.

Considering a hybrid kitting system, where the operator and the robot work in two separate areas, the number of kit packages located in the middle of the two areas, must be sufficient to decouple the work of the operator from that of the robot. One solution that could be used, is one that considered a stationary kit cart for the robot, positioned at the end of the aisle and a second moving cart for the operator, who moves it in front of him, every picking tour, like can be seen in the current Figure 9. Otherwise you could think of positioning the kit packages in an intermediate zone between the manual and robotic kitting area, so that the robot and the operator can work simultaneously in the preparation of the same set of kits.

3. Methodology

This chapter describes and motivates the research methods that are used in the three research questions. All three research questions have been formulated with the aim of trying to obtain considerable results on the analysis of the kitting area, in terms of how design variables and contextual factors influence the performance of the hybrid kitting system, in which an operator and a robot are working together with the scope of preparing a number of kits. The kits preparation supplies a mixed-model assembly line, in which will be assembled some end products.

3.1 - Methodology for research question 1

For introduce the method utilized to answer the research question 1, it must be underlined that kit preparation system is complex and they involve numerous variables of potential importance to the time-efficiency of the hybrid kits preparation.

The first step of the study is to propose a set of aspects that could potentially influence the time-efficiency of the hybrid kits preparation. This was based firstly on a comprehensive review of the existing literature but also on the input of some staff from the laboratory, who had great experience about kits preparation. The selection of the literature analysed was based primarily on a search on "*Google scholar*" by entering as keywords the terms related to kitting, order picking, materials feeding, hybrid kitting system, robotic kitting and others. After that, attention was paid to the references of each article related to the topic in question.

The reviewed literature included studies focussed on kitting and on the choice between kitting and other materials feeding principles (Bozer and McGinnis, 1992; Caputo and Pelagagge, 2011; Limère *et al.*, 2012; Hanson and Medbo, 2012; Caputo *et al.*, 2015a; Caputo *et al.*, 2015b; Limère *et al.*, 2015; Sali and Sahin, 2016; Caputo *et al.*, 2018). The literature dealing with picking activities was also reviewed, including literature on picking at assembly work stations (Finnsgård and Wänström, 2013). Some of the reviewed papers focus explicitly on the performance of kits preparation with regard to the design of the picking system (Brynzér and Johansson, 1995; Hanson *et al.*, 2011; Hanson *et al.*, 2015). Most of the literature analysed is based on the analysis of *manual* kitting system, in which the operator has prepared the kits, taking the components from the storage and placing them in the appropriate kit packages. However, the focus was mainly on the few papers available on the *hybrid* kitting system, in which the operator collaborates with the robot in the preparation of the kits (Boudella *et al.*, 2018; Coelho *et al.*, 2018; Fager, 2019) and also on the *robotic* kitting system (Boudella *et al.*, 2017a).

The second step of the study was to identify aspects of particular importance to the time-efficiency of the hybrid kits preparation. This selection of the important aspects was based on personal considerations by the author and through focused groups with the qualified staff of the Stena Industrial Innovation laboratory "SII-lab". Afterwards, the influence of these factors on the time-efficiency of the hybrid kitting system was evaluated basis on the analysed literature.

3.2 - Methodology for research question 2

The aim of research question 2 is to create a model for the classification of components, based on their physical characteristics, so as to understand which of them can be suitable for picking by the robot and which are suitable for picking by the operator. Subsequently, the assumptions deriving from the theoretical model will have to be confirmed by experimental evidence, in which some tests will be planned to confirm what is said in the theoretical model. The steps necessary to create the model are explained in the following paragraphs. First, an analysis of the components available in "Stena Industry Innovation Laboratory" was carried out, observing their physical characteristics. At the same time the literature concerning the categorization of the components was analysed (Caputo, Pelagagge and Salini, 2018b), (Hanson and Medbo, 2016), (Hanson and Medbo, 2019). Subsequently, following the purpose of research question 2, there was the need to find useful parameters in the classification of components according to their physical characteristics. These parameters with which the components were classified were derived from a literature analysis but also on the input of some staff from the "SII-lab: Stena Industry Innovation Laboratory", who had great experience of kits preparation. Finally, the classification parameters present in the theoretical model are: size, weight, shape, planar surface, material, fragility, stiffness, tangling attitude and fullness.

Once the theoretical model has been defined, the objective of the research question 2 is to verify or not experimentally the consideration derived from the theoretical model. For this purpose, some laboratory tests have been defined. The methodology used for the definition of these tests includes some steps, which are explained in more detail in the sub-section 3.2.1 - 3.2.3:

i. Analysis of parameters for the component's classification
ii. Case selection
iii. Description of laboratory tests

3.2.1 - Analysis of parameters for the component's classification

First of all, the author, by making a selection of the parameters in the theoretical model, has chosen the parameters that correspond to physical characteristics, which allow to analyze the available components. Secondly, specific intervals have been defined for each characteristic. The criteria for choosing both the parameters to be analysed and the internal ranges for each parameter were based on personal considerations by the author, so as to have a good distribution of cases for the various characteristics selected. Each case corresponds to the analysis of a specific SKU.

More specifically:

- the "**Size**" has been divided in 3 intervals: big (size > 70mm), medium (20mm < size < 70mm) and small (size < 20mm);
- the "**Weight**" has been divided in 3 intervals: High (w > 1000g), medium (100g < w < 1000g), low (w < 100g);
- the "**Shape**" has been divided in 2 macro-divisions:
  - **Non-geometrical shape**: includes all those irregular shapes not definable by some combination of geometrical elements;
  - **Geometrical shape**: includes all those shapes like for example prism, cylinder or definable by some combination of geometrical elements. This sub-category has been subdivided in turn by 3 divisions: shape similar to a prism - shape similar to a cylinder - other shapes with some symmetry within them resulting from the combination of known geometrical elements.
    The cylindrical components are differentiated by their "radius of curvature" and are divided into 3 intervals:
    - Wide radius: radius > 1,5*D_{vg} "Diameter of vacuum grip" (D_{vg} is about 27mm);
    - Medium radius: 0,6*D_{vg} < radius < 1,5*D_{vg};
    - Small radius: radius < 0,6*D_{vg};

- the "**Planar surface**" is meant as the extension of the planar surface without the presence of steps or holes and has been divided in 3 intervals:
  - **Large**: when it is possible to inscribe a circle on the planar surface with the diameter "d" such that: $d > 2*D_{vg}$;
  - **Medium**: $1* D_{vg} < d < 2* D_{vg}$;
  - **Low**: $d < D_{vg}$;
- the "**Fullness**" has been divided in 2 intervals:
  - **Full**: is meant as the property of the component to be composed of material and to have no cavities inside it.
  - **Hollow**: the component presents a concave surface inside it;
- the "**Fragility**" has been divided in 2 intervals:
  - **Fragile**: is intended as a component that both because of the material of which it is composed and because of its physical characteristics could break while being handled, so it needs to be packed in a plastic wrap to protect it from shocks.
  - **Non-fragile**: is intended as a component that doesn't need to be packed in a plastic wrap.
- the "**Stiffness**" has been divided in 2 intervals:
  - **Deformable**: is intended as a component that due to the material which with it's made, it can deform itself under a pressure.
  - **Stiff**: is intended as a component which, despite the application of some pressure forces, it doesn't deform and its original size remain unchanged.

Note: the "radius of curvature" and "the diameter of inscribe circle in the planar surface" needs to be indicated according to the diameter of the vacuum grip both to be able to draw useful considerations from the results and to be able to generalize as much as possible the choice of these ranges and to give the possibility to use these values also for other applications where different grip sizes are used. In general, the width of each range was decided on the basis of the availability of components in the laboratory.

3.2.2 - Case selection

Based on the previous characteristics that have been chosen to analyse in the current experiments, 30 cases were selected (15 cases for vacuum grip and 15 cases for fingers grip) in which the different aspects could be studied. Each case consisted of a component, on which the success or otherwise of the grasp by the grip was tested.

In total, a several number of cases (30 cases) have been analysed for having a possibility to test each characteristic in different types of components, as can be intuitively seen from Table 1 and Table 2, that show the variety of the cases selection for each type of grip. It must be underlined that the choice of components also took into account the fact that you want to take the grip to the limit, testing components with physical characteristics that challenge the grip in taking them.

Practically, each case was evaluated according to the physical characteristics selected in subsection 3.2.1 and a cross was placed in the appropriate range of each parameter (Table 1 and Table 2). It must be underline that some cases were tested both by the vacuum grip and the fingers grip.

Table 1 - Case selection for vacuum grip. The parameters on the left column are defined in the Section 3.2.1.

				Cases														
Characteristics				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Size	Big			x	x	x				x	x	x			x			x
	Medium						x	x	x				x	x			x	
	Small															x		
Weight	High				x		x			x								
	Medium			x				x				x			x			
	Low					x			x		x		x	x		x	x	x
Shape	Non-Geometrical					x				x		x						
	Geometrical	Prism			x				x						x			x
		Cylinder: Radius of curvature	Wide								x		x					
			Medium														x	
			Small											x		x		
		Other		x			x	x										
Planar surface	Large									x	x							x
	Medium				x	x	x	x	x				x	x			x	
	Small			x								x			x	x		
Fragility	Fragile									x							x	
	Not Fragile			x	x	x	x	x	x		x	x	x	x	x	x		x
Stiffness	Deformable					x												
	Stiff			x	x		x	x	x	x	x	x	x	x	x	x	x	x

Table 2 - Case selection for fingers grip. The parameters on the left column are defined in the Section 3.2.1.

Characteristics				Cases														
				16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Size	Big			X	X					X	X	X						X
	Medium					X		X	X					X		X	X	
	Small						X						X		X			
Weight	High			X		X												
	Medium							X		X		X						
	Low				X		X		X		X		X	X	X	X	X	X
Shape	Non-Geometrical				X								X	X				
	Geometrical	Prism		X					X			X					X	
		Cylinder: Radius of curvature	Wide							X	X							
			Medium													X		
			Small												X			
		Other				X	X	X										X
Fullness	Full					X	X	X	X			X	X	X	X		X	
	Hollow			X	X					X	X					X		X
Fragility	Fragile																	
	Not Fragile			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Stiffness	Deformable				X											X		
	Stiff			X		X	X	X	X	X	X	X	X	X	X		X	X

3.2.3 - Description of laboratory tests

In this section the laboratory tests have been described. The aim of these trials is to test which component characteristics allow the picking with a specific type of grip and which component are suitable for manual picking by operator. In particular these tests want to analyse the ability of two type of grip (vacuum grip and fingers grip) in grasping various type of components with different characteristics.

Every case in which the grip tried to grasp a certain component was recorded by a camera. Subsequently, the video was analyzed with the aim of evaluating whether or not the picking was successful. Finally, after having marked the results in an appropriate Table 5 and Table 8 (Chapter 4), the author was able to make considerations regarding the results of the experiments.

This approach is very laborious and time-consuming for the operator to analyse all the videos. However, an automated vision system would only be able to detect whether picking was successful or not, but not, for example, the cause that prevented the component from being grabbed correctly.

3.3 - Methodology for research question 3

The aim of the research question 3 is understanding how contextual factors can influence the time-efficiency performance of the hybrid kitting system. The context of the kits preparation system is viewed as everything that is beyond the direct influence of the designers of the kits preparation system. In this thesis is assumed, as is often the case in the industry, that the contents of the kits (representative of the context) are decided mainly by the production engineers, responsible for designing the assembly stations receiving the prepared kits, rather than the designers of the kits preparation system.

The first step is to propose a set of factors related to the context that could potentially influence the time efficiency of the hybrid kits preparation. This was based firstly on a comprehensive review of the existing literature but also on the input of some staff from the laboratory, who had great experience of kits preparation. Subsequently, a selection of these factors was necessary, trying to focus on those factors that had found great interest in the literature, taking the attention away from all the others. A selection of contextual factors was necessary due to operational constraints that prevented us from testing all aspects of the context previously found. Once arrived at a limited number of factors to be considered, through comparison meetings with both the laboratory staff and the thesis supervisor, three contextual factors that have been analysed through experiments in the laboratory were defined. In this selection of factors, the feasibility of carrying out the appropriate experiments in the laboratory was also taken into account. At the end of the selection process the three contextual factors that have been analysed are: **the number of components per SKU**, **the component size** and **the easiness of grasping**.

3.3.1 - Setup of the kitting system

Practically the experiments were carried out using a smaller robot that the one you would use in a real application, easy to program, having all the functions of the real robot, but limiting in terms of range, weight and size of the components to be taken. In the Figure 10 is shown “Yaskawa” robot that is used in some industrial application, and in the Figure 11 it can be seen a small version robot, that is used in the current experiments.

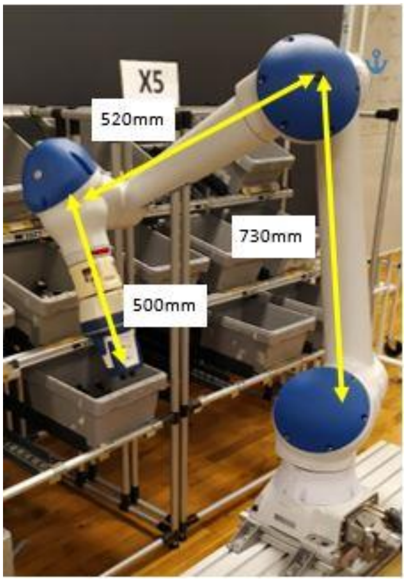


Fig. 10 - Measurement of real robot arm.

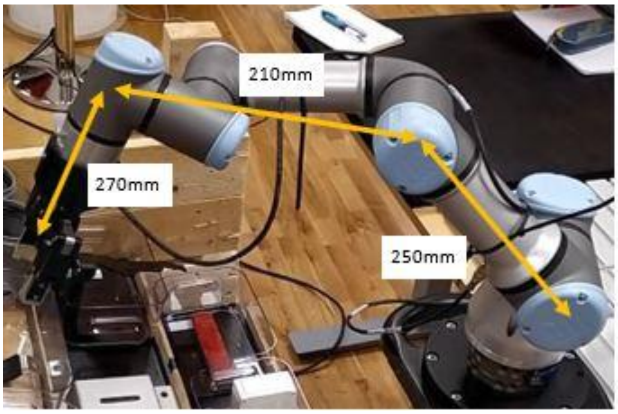


Fig. 11 - Measurement of small robot arm.

A ratio R has been calculated between the range of actions of the 2 versions of robots. In particular:

$$R = \frac{Big\ robot\ arm\ lenght}{Small\ robot\ arm\ lenght} = \frac{500 + 520 + 730}{270 + 210 + 250} = \frac{1750\ mm}{730\ mm} = 2{,}4$$

To analyse all the parameters, present in a real application, it was necessary to develop and build in the laboratory a model of the storage rack and stationary cart for the kit packages. The dimensions were derived from the original storage, using a scale factor calculated above. To be accurate it should be derived the ratio between the workspace of the big robot and small robot. Since this specific setup is not the focus on this thesis, a rough estimation of the proportion between the two robots was derived using the two-maximum elongation of the robot’s arm. The Figure 12 and Figure 13 show the model of 3-levels rack build in the SII-laboratory by the author, while Figure 14 shows the rack already present in the laboratory.

Fig. 12 - Work in progress of building the small scale 3-levels rack.

Fig. 13 - Finish model of the small-scale 3-levels rack.

Fig. 14 - 3-levels rack used in the real application.

The small-scale storage rack contains twelve kit packages with the same size (200mm x 140mm x 75mm). The size of the kit packages was decided in such a way as to contain all the components necessary for the preparation of one kit.

3.3.2 - Setup of the experiments

In this section the set-up of the experiments regarding the research question 3 is defined. In these experiments the contextual factors varied once a time:

- Contextual factor 1: Number of components per SKU;
- Contextual factor 2: Component Size;
- Contextual factor 3: Easiness of grasping;

For each contextual factor a several numbers of tests were carried out, each of which involving the preparation of a different kit with a specific composition. This is done in order to obtain an average value of the time needed to kit a single component and a range of variability of this value (standard deviation). More specifically the number of kits for each contextual factors sub-section that have been analysed is shown in the Table 3.

Table 3 - Number of kits analysed for each contextual factor's sub-section.

Contextual factor		Number of kits
Number of components per SKU	1 component per SKU	6
	2 component per SKU	6
Component Size	Big size	6
	Medium size	6
	Small size	6
Easiness of grasping	Easy grasping	6
	Medium difficult grasping	6
	High difficult grasping	6

The average value for kit a single component was calculated by the current formula:

$$Average\ time\ to\ kit\ a\ single\ component = \frac{Total\ time\ to\ prepare\ a\ kit}{Number\ of\ components\ per\ kit}$$

It must be noted that the number of components per kit means the number of parts contained in one kit. Each test is characterized by a specific disposition of the components on the storage rack. Each storage package placed on the storage rack is identified by a number, as can be seen in Figure 15, which shows an example of disposition. Each composition of the kits with which the various tests were performed is shown in Appendix A. Noted that all the tables in the Appendix A show number which are referred to Figure 15.

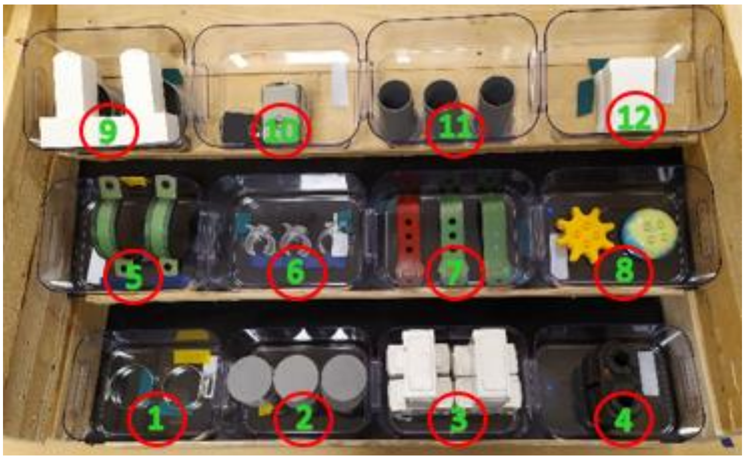


Fig. 15 - Example of component's disposition.

In addition, the research question 3 includes also the analysis of the average time to kit a single component, between SKUs that are suitable for both vacuum and fingers grip.
The SKUs that are suitable to be grasped with both vacuum grip and fingers grip were defined, based on the results of the Section 4.2. Once these components have been found, one combination of twelve components - randomly chosen among the ones suitable for both grips - have been created. Using these components, a number of kitting tests, each contained 4 components, have been carried out. More specifically, in order to obtain statistical data such as average and standard deviation, the number of kits for each sub-section that have been analysed is six. The average time to kit a single component has been calculated using the same formula of the previous experiments. Note that, in order to properly compare the two types of grip, the experiments were carried out with the same SKUs for both the vacuum grip and the fingers grip.

3.3.3 - Procedure

Each of the cases, resulting from the variants in which each experiment is articulated, was studied by use of video recording. After by using elementary software called "ATM", the author thoroughly reviewed each video recording and noted predetermined activities were performed and when each of these activities started and stopped. The activities included in this analysis was: reaching out to the rack, grasping the component from the storage package, reaching out the kit cart, placing the component into the kit package. Thus, the output of this initial analysis was, for each case, a description of the work into the predefined activities, in which the time consumption for each activity was registered. Subsequently in the data review, the time taken by the robot to reach the rack and to bring the component from the storage rack to the kit cart was considered as a unique activity. Once the duration of time for each activity has been determined, the average time per kitting a single component is calculated, dividing the time needed to complete a kit by the number of components in the kit. It must be underline that the kitting time is the sum of picking time, travelling time and placing time. It has also been calculated the average time respectively for the picking, travelling or placing activity, by averaging these partial times for the various components of each kit.

3.4 - Overview of the methodology

The overview of the methodology used for study the three research questions is shown in the Table 4.

Table 4 - Overview of the methodology for study the three research questions

Research question	Input	Answer method	Output
Research question 1: "*How does the design variables influence the time-efficiency in hybrid kits preparation?*"	Previous literature: material feeding principle, assembly, *manual* kitting, *hybrid* kitting, *robotic* kitting.	Literature analysis	Theoretical analysis about the influence of each design variables on the time-efficiency of the hybrid kits preparation.
Research question 2: "*Which component characteristics affect components suitability for picking by robot and operator, respectively?*"	Previous Literature: categorization of components. Analysis of laboratory components.	Literature analysis + Experiments	Model of the categorization of the components based on their characteristic. Experimental validation of the theoretical categorization.
Research question 3: "*How does the contextual factors influence the time-efficiency in hybrid kits preparation?*"	Previous literature: *manual* kitting, *hybrid* kitting, *robotic* kitting.	Literature analysis + Experiments	Numerical results show the influence of contextual factors on the time-efficiency of the hybrid kits preparation. Analytical model that aims at optimal distribution of work between robot and operator and estimate the kit preparation cycle time.

4. Analysis and discussion of results

This chapter presents the results of the thesis as responses to the research questions. The chapter is structured by the responses to each research question, where Section 4.1 provides the response to research question 1, Section 4.2 provides the response to research question 2 and Section 4.3, Section 4.4 and Section 4.5 provide the response to research question 3. Finally, Section 4.6 provides a general discussion of the results.

4.1 - The influence of design variables on the time-efficiency

Research question 1 concern the influence of the design variables on the time-efficiency performance and is restated here for reference:

Research question 1:
How does the design variables influence the time-efficiency in hybrid kits preparation?

The aspects to the design variables that are considered in this analysis are:

- Size of the picking area: width and length of aisle;
- Operator/robot job role;
- Storage policy;
- Batching policy;
- Picking policy;
- Storage package design;
- Information system type;
- Storage rack design;
- Kit cart design;

4.1.1 - Layout

- **Size of the picking area: width and length of aisle**

  De Koster *et al.*, (2007) have supposed that travel issues, as the large amount of walking distance that the operator has to cover along the aisle of the warehouse, are applicable mainly to contexts of large picking areas and many part numbers. While a small area makes the travel distance short and almost constant from round to round. In such an environment, the importance of the time spent on the actual picking operations increases in relation to the importance of the time spent travelling through the kits preparation area.

Since the length of the aisle is directly linked to the width of the storage packages; if this width is increased, the storage will become longer, increasing the distance to be travelled by the operator and therefore the travel time that will negatively affect the time-efficiency (De Koster *et al.*, 2007). From these considerations you can intuitively deduce how the size of the kitting area is closely related to the size of the storage packages.

In all literature analysed, the "high picking density" plays a key role in reducing the kitting time, in favour of the time-efficiency: the average distance traversed between picks could be as small as possible. So, the goal of the picking area designer, should be to compact it as much as possible.

4.1.2 - Work organisation

- **Operator/robot job role**

  Considering the hybrid kitting system shows in (Boudella *et al.*, 2018), the optimal solution is found assigning to the robot the picking, travelling and placing tasks, while assigning to the operator also the load of empty kit packages and unload of full kit packages. For this reason, considering that the operator's velocity is slightly higher the robot's velocity, will be assigned to the operator fewer SKUs than the robot, for having enough time to complete these additional activities.

  Fager (2019) have analysed the comparison between manual and cobot-supported kits preparation in terms of the time-efficiency of the kits preparation, which is central for the kits preparation in industrial settings. The findings suggest that the use of cobots to support the sorting task in kits preparation offers a higher time-efficiency for low to moderate amounts of components to be sorted per SKU, and this is results in a more stable outcome than kits preparation performed manually.

4.1.3 - Policy

- **Storage policy**

  In their experiments, Brynzér and Johansson (1995) have confirmed that the travel time in manual kitting area (constitute about 15-25% of the total kitting time), can be reduce using the product structure and assembly schedule to assign components to storage locations.

- **Batching policy**

  Brynzér and Johansson (1995) have discussed numerous aspects of kits preparation, including the batching policy. One aspect they do mention is that preparing kits in batches can potentially increase man-hour efficiency by reducing both travel distances and direct picking times, but can also increase the amount of sorting and administration compared to making one kit at a time.

  According to Yu and De Koster (2009), the main objective of batching in the context of kitting is the reduction of the travel time for the picker, but Brynzér and Johansson (1995) state that the average picking and placing time can also be reduced. Often, an important aspect of batching is the grouping of orders to create batches with similar contents, according with the assembly sequence.

  From the results of the experiments carried out by (Hanson *et al.*, 2015) it was obtained that the batches were meant to be as large as possible without compromising the possibility of efficiently handling the kit cart. The experiments show that the batch preparation requiring less preparation time than the single-kit preparation, according with the theoretical evidence.

  One consequence of the use of batch preparation is that it often allows the picker to grab several components of each part number simultaneously and, thereafter, distribute them among the different kit packages. However, in some sense batching also causes a more complex picking, including the design of the picking information, which can have a negative effect on the picking accuracy (Brynzér and Johansson, 1995).

  It should be noted that there could be further benefits of batch preparation in addiction to what was observed during the experiments. While the analyses of the experiments focused only on the activities directly associated with the picking of components, other activities, such as handling kit containers and walking back after each cycle, could also potentially benefits from batch preparation (Hanson *et al.*, 2015).

- **Picking policy**

  In the previous literature, there isn't an empirical evidence about how picking policy influence the time-efficiency. However, it is possible to make a few observations in this regard. If the content of the different kits in a batch differ greatly, then the benefits associated with batching could be reduced, as there are fewer opportunities for the picker to grab several components at once.

4.1.4 - Packaging

- **Storage package design**

  The type of storage packages has a significative impact on manual picking time (Finnsgård and Wänström, 2013). The size of the storage package should be large enough to contain all the components needed to complete the batch, always tending to use the smallest possible packages.

  Different packaging size of storage packages were used for different levels of picking density. The reasoning behind that approach was that larger sized packages contributes to longer walking distances, thereby lowering picking density as well as time efficiency. (Fager, 2019).

4.1.5 - Picking information

- **Information system type**

  The picking information system can considerably affect the picking time. Fager (2016) have analysed four principal different picking information system types: Pick-by-list, Pick-by-light, Pick-by-vision, Pick-by-voice. With single-kit preparation, the Pick-by-light system was associated with the highest time efficiency. The reason is that the Pick-by-light system is associated with a simultaneous occurrence of "Get information" and "Search", which means that the operator knows both what and where to pick by light on the storage rack. In contrast, the other three information system requires retrieving the information first and subsequently identifying the storage location. For batch preparation, Pick-by-list was associated with the highest time-efficiency. A likely explanation is that all the other systems required confirmation associated with the picking location and the kit-packages.

4.1.6 - Equipment

- **Storage rack design**

  In the model expressed by (Boudella *et al.*, 2018), the robot's rack, in the most part of cases, has 2-levels due to the limit range of its range. If you could get the robot to

work using a 3-level rack, the storage will be more compacted and you will achieve a high picking density, which, as confirmed by other studies, (Hanson and Medbo, 2016) increases the time-efficiency. However, Hanson and Medbo (2019) shows that using three shelf levels rack with large offset related the lower picking density, with shorter picking time was been obtained.
The angle of exposure of a storage package influence both manual and robotic picking time. Intuitively, when the storage package is located on the higher level of the rack, the more the container will need to be inclined to facilitate entry of the robotic arm and the operator's hand. Especially when you are dealing with small components and there are few items in the package and you have to go to the bottom of the package to grab those components (Hanson and Medbo, 2016; Hanson and Medbo, 2019).

- **Kit cart design**

  Some experimental evidence has shown that using a mobile cart containing the kit packages, pushed by the operator during its route, instead of a fixed cart positioned at the beginning of the island, reduces the time needed to move a component from the rack to the kit package, and therefore has a positive effect on time-efficiency (Hanson and Medbo, 2016; Hanson and Medbo, 2019).

4.1.7 - Summary of the main results related to the research question 1

In this section, Table 5 shown a summary of the results of the research question 1.

Table 5 - Summary of research question 1: "How design variables influence the time-efficiency".

Design variables	Performance	Direction of influence	Description of influence
Size of the picking area	Time-efficiency	Negative with increasing size of the picking area	If the size of the picking area increases, the distance to be travelled by the operator and the robot increases, as well as the travel time related to time-efficiency.
Operator/ robot role	Time-efficiency	Positive with increasing robot task	The use of a robot in the preparation of the kits slightly reduces the time needed for kits preparation, whether it performs a picking or sorting task.
Storage policy	Time-efficiency	Positive with increasing dedicated storage policy	The use of a dedicated storage policy, using a fixed location for each component, according to the frequency of use and the product structure, increase the time-efficiency.
Batching policy	Time-efficiency	Positive with increasing batching policy	The batch preparation requires less preparation time than the single-kit preparation, because it reduce both travel distances and direct picking times.
Picking policy	Time-efficiency	(No influence)	(No influence)
Storage package	Time-efficiency	Negative influence with increasing storage package size	The storage package size is related to the lenght of the picking aisle that negatively influence the time-efficiency.
Information system	Time-efficiency	Positive influence with using the Pick-by-light system	The Pick-by-light system is associated with the highest time-efficiency.
Storage rack design	Time-efficiency	Positive influence with using the 3-levels rack	Using a 3-levels rack, the storage is more compacted, increasing the picking density, positively related to the time-efficiency.
Kit cart design	Time-efficiency	Positive influence with using the mobile cart	If the kit packages are positioned on a mobile kit cart, the time needed to move a component from the rack to the kit package is lower the using a fixed cart.

4.2 - Categorization of the components

Following sub-section concern the categorization of the components. More specifically, the sub-section 4.2.1 speaks about the theoretical model of the categorization, the sub-section 4.2.2 concern the experimental validation of the theoretical model and in the sub-section 4.2.3 there is a summary of the main results related to this section.

4.2.1 - Categorization theoretical model

Research question 2 concerns the categorization of the components based on the physical characteristic and is restated here for reference:

Research question 2:
Which component characteristic affect components suitability for picking by robot and operator, respectively?

The categorization has the double purpose, both to understand which components to assign to the operator and which to the robot, and (only for the robot) to choose the type of grip best suited to the grasp of each component.
The categorization is based on previous literature (Boudella *et al.*, 2018; Hanson and Medbo, 2016; Hanson and Medbo, 2019; Brynzér and Johansson, 1995; Caputo and Pelagagge, 2011; Limère *et al.*, 2012; Limère *et al.*, 2015; Caputo *et al.*, 2015a; Caputo *et al.*, 2015b; Caputo *et al.*, 2018; Limère *et al.*, 2015).

Categorization by components **physic characteristic**:

1) ***SIZE***:
    a. **Big**: mainly suitable for the operator. The vacuum grip could be suitable for big size components as long as there is a sufficiently wide planar surface to create the vacuum. However, the operator in some cases, is more appropriate because he is more flexible and he has a wider range of action than robot.
    b. **Medium**: suitable for both the robot and the operator, depends on shape complexity, size and weight, that they are extremely related to the easiness of grasping. For example, if the component has a geometrical shape (like cylinder or prism) it could be suitable for robot, while if it has a complex shape, it is suitable for operator.

c. **Small**: suitable for both the robot and the operator, depends on how many items operator can pick in one time. So, we have to reach an economic compromise. Regardless, with small size components, robot can only use the fingers grip because is more practical and the vacuum can't work without large planar surface.

2) ***WEIGHT:***

a. **High**: mainly suitable for the operator because he has greater capacity to lift high weights than the robot. However, the robot can help the operator grasping all those components whose weight does not exceed the maximum limit of weight, specific to each type of grip. Components heavier than this limit must be assigned to the operator.

b. **Medium**: suitable for both the operator and the robot. The weights significantly lower than the limit of each grip, do not create any problems in grasping of the component.

c. **Low**: suitable for both robot and operator.

3) ***SHAPE:***

a. **Non-geometrical**: when the component has a shape that is not easily defined like a combination of geometrical elements or it can be visibly deformed (e.g. rubber components), the picking action is more suitable for the operator who has better sensory-motor capabilities than the robot.

b. **Geometrical**: when the component has a geometrical shape like a prism or cylinder or otherwise definable as a composition of known geometrical elements, robot could easily do the picking task. In particular is shape is more similar to:

   i. ***Prism***: it is recommended to use vacuum grip, because it is suitable for components that they have a large plane surface;

   ii. ***Cylinder***: it is recommended to use finger grip because it can adapt for picking components in different positions.

4) ***PLANAR SURFACE:***

a. **Large planar surface**: considering only the use of robot, for components that have a large planar surface, it is recommended to use the vacuum grip, because it allows to pick the component quickly and without hesitation.

b. **Small planar surface**: considering only the use of robot, for components that have a small planar surface it is recommended to use the finger grip, because it can better adapt to the characteristics of the component.

5) ***MATERIAL***:

a. **Ferromagnetic**: considering only the use of robot, for components made by a ferromagnetic material, it would be useful to use the magnetic grip. You have to pay attention to the size of the components, as it may happen that, if the components are too small, the grip may take several components at once, without taking into account the number of components taken.

b. **Non-ferromagnetic**: in this case robot could grip components with vacuum or finger grip.

6) ***FRAGILITY***:

a. **Fragile (need a cover like a plastic wrapper)**: suitable for operator because he is able to understand the contents of the wrapping without any particular problems. the robot instead would have some problems with its vision system, which would not be able to identify the contents of the wrapping and how to grasp the component.

b. **Non-fragile (don't need a cover)**: suitable for both the robot and operator.

7) ***STIFFNESS:***

a. **Stiff**: the stiff components are suitable for gripping by the robot, because under the action of the clamps they do not deform and above all, the grip remains solid and stable throughout the robot's movements.

b. **Deformable**: deformable components could put the robot in difficulty either because it could plastically deform the component if too much force was applied between the fingers of the grip, or because the component could be grasped insecurely and therefore drop down from the grip. Reason for that, the deformable components are more suitable for the operator.

8) ***TANGLING ATTITUDE:***

a. **Tangle**: with the tangled components, when the robot picks up a component, it also pulls up other components that are tangled up with the first one. These components are in fact suitable for picking by the operator, who using both hands can release the components, and take the exact amount.

b. **Non-tangle**: with non-tangled component, the robot will have no problem in picking up the correct number of components, so these components are suitable for both the operator and the robot.

9) ***FULLNESS:***

a. **Full**: considering only the use of the robot, the full components are suitable for both vacuum and fingers grip, depends on their shape.

b. **Hollow**: considering only the use of the robot, the hollow components are suitable for the fingers grip, for the reason that it can grasp the component on its edge, going into the cavity with one finger.

4.2.2 - Model experimental confirmation

In this sub-section, the experiment's results about the confirmation of the previous categorization are shown. More in details in the sub-sections 4.2.2.1 and 4.2.2.2 there are the results about the experimental confirmation of the theoretical model related to the vacuum grip and fingers grip respectively.

4.2.2.1 - Results related to the vacuum grip

In the current Table 6, the results of the grasping tests relating to vacuum grip are reported.

Table 6 - Results of picking test related to the vacuum grip.

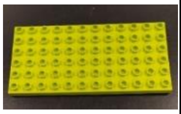
				Cases														
Characteristics				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Size	Big			x	x	x				x	x	x			x			x
	Medium						x	x	x				x	x			x	
	Small															x		
Weight	High				x		x			x								
	Medium			x				x				x			x			
	Low					x			x		x		x	x		x	x	x
Shape	Non-Geometrical					x				x		x			x			
	Geometrical	Prism			x				x									x
		Cylinder: Radius of curvature	Wide								x		x					
			Medium														x	
			Small											x		x		
		Other		x			x	x										
Planar surface	Large									x	x							x
	Medium				x	x	x	x	x				x	x			x	
	Small			x								x			x	x		
Fragility	Fragile									x							x	
	Not Fragile			x	x	x	x	x	x		x	x	x	x	x	x		x
Stiffness	Deformable					x												
	Stiff			x	x		x	x	x	x	x	x	x	x	x	x	x	x
Picking success				NO	NO	YES	YES	NO	YES	NO	YES	NO	YES	NO	NO	NO	YES	YES

Table 7 and Table 8 show in detail the result of each test with comments and reasons for the success or otherwise of the attempt to grasp the component by the vacuum gripper.

Table 7 - Results of grasping test by vacuum grip.

Case	Type of grip	Picture	Picking success	Motivation of picking success/failure	Crucial physical characteristic
1	Vacuum		NO	Even if this component has big size, the planar surface is small and the vacuum can't work.	Small planar surface
2	Vacuum		NO	The surface of this components has many holes, so the grip needs to decentralised the grasping position that, considering also the big component weight, it generates a flexion torque to the grip and vacuum can't work.	Big size - big weight - medium planar surface
3	Vacuum		YES	Even if the component is made by rubber and it doesn't the same shape into the storage package, its medium planar surface combining to its low weight, allows the grip the pick it.	Medium planar surface - low weight
4	Vacuum		YES	This component has a geometrical shape with a medium planar surface and despite its weight is high, the vacuum grip can pick it both in the middle and in an oblique side.	Geometrical shape - medium planar surface
5	Vacuum		NO	This component has a particular geometrical shape that often doesn't allow it to have a perpendicular surface to the floor. This fact combining with its medium weight often makes the vacuum grip fails.	medium weight - particular shape
6	Vacuum		YES	This component has a very low weight a simple geometrical shape. However, its planar surface is a little bigger than the grip surface so the grip have to grasp the component in a very precise position.	Medium planar surface - low weight
7	Vacuum		NO	This component has a plastic wrapper around it for preserve its integrity and the wrapper doesn't allow the grip to attach well to the component surface and thereby the vacuum can't work, also considering its high weight.	Fragile component - high weight
8	Vacuum		YES	Even if this component has a cylindrical shape, the vacuum grip is able to pick it, because the radius of curvature is wide and locally there is enough planar surface to allow the vacuum grip to work.	Wide radius of curvature - low weight

Table 8 - Results of grasping test by vacuum grip (continued)

Case	Type of grip	Picture	Picking success	Motivation	Crucial physical characteristic
9	Vacuum		NO	This component has a complex non-geometrial shape, reason for that there isn't an enough large planar surface for allow the grip to grasp the component.	Small planar surface - Non-geometrical shape
10	Vacuum		YES	This component has a cylindrical shape with a wide radius of curvature and a medium planar surface that allows the vacuum grip to work.	low weight - Wide radius of curvature - medium planar surface
11	Vacuum		NO	This component has a cylindrical shape with a too small radius and despite the very low weight, the grip can't pick it.	Small radius of curvature
12	Vacuum		NO	Its surface, despite being very wide, has several features that do not allow you to have a horizontal planar surface on which the grip can pick the component.	Small planar surface - Non geometrical shape
13	Vacuum		NO	The size of this component is too small for allows the vacuum grip to work.	small size
14	Vacuum		YES	It has a cylindrical shape with a medium radius of curvature that combined with a low weight allows the grip to pick it with very carefully	medium radius of curvature - low weight
15	Vacuum		YES	It is a big size parallelepiped, so it has a large planar surface in all of its sides. So it's perfect for the vacuum grip.	Large planar surface - low weight

As can be seen from the Table 5, Table 6, Table 7, the vacuum grip is not suitable for grasping all those components which, due to their small size or their particular shape, have a small planar surface (cases 1, 9, 11, 12, 13). It is evident how other physical characteristics can be connected to the "small planar surface" such as the small size, the small radius of curvature and the fact of having appendages that prevent having a planar surface on which the vacuum grip can easily attach.

In cases 2 and 5, it can be noted that although there is a medium planar surface suitable for the use of vacuum grip, the latter is not able to grasp the component because due to both the high weight and the impossibility of grasping the component near its center of gravity, the grip is not able to adhere firmly to the component so that it can be lifted stably.

The best condition for vacuum grip is when a component has a large planar surface and a low weight. Clearly having a large planar surface is linked to having a prismatic geometric shape (case 15). Other conditions are close to the ideal one, in which the components have a medium planar surface and a geometric shape that allows the component to be grasped near its center of gravity (cases 3, 4, 6, 8, 10, 14).

Finally, it is possible to evaluate the case in which even though the component has a large planar surface, the vacuum grip is unable to grasp it due to the fact that the component, being fragile, has a plastic wrapper to protect it from shocks, which doesn't allow the vacuum to work (case 7).

In all cases where the success of the picking is negative, this component should be assigned to the operator, who with his high sense-motor skills will be able to grasp the components.

4.2.2.2 - Results related to fingers grip

In the Table 9, the results of the grasping tests relating to fingers grip are reported.

Table 9 - Results of picking test related to the fingers grip

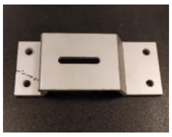
				Cases														
Characteristics				16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Size	Big			X	X					X	X	X						X
	Medium					X		X	X					X		X	X	
	Small						X						X		X			
Weight	High			X		X												
	Medium							X		X		X						
	Low				X		X		X		X		X	X	X	X	X	X
Shape	Non-Geometrical				X								X	X				
	Geometrical	Prism		X					X			X					X	
		Cylinder: Radius of curvature	Wide							X	X							
			Medium													X		
			Small												X			
		Other				X	X	X										X
Fullness	Full					X	X	X	X			X	X	X	X		X	
	Hollow			X	X					X	X					X		X
Fragility	Fragile																	
	Not Fragile			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Stiffness	Deformable				X											X		
	Stiff			X		X	X	X	X	X	X	X	X	X	X		X	X
Picking success				NO	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO

Table 10 and Table 11 show in detail the result of each test with comments and reasons for the success or otherwise of the attempt to grasp the component by the fingers gripper.

Table 10 - Results of grasping test by fingers grip

Case	Type of grip	Picture	Picking success	Motivation	Crucial physical characteristic
16	Fingers		NO	This component is very difficult to grasp with the fingers grip, because it's very heavy and the smooth surface doesn't allow the fingers to keep a solid grip because it slips with respect to it.	Big weight
17	Fingers		NO	This component being composed of rubber is deformable, so it deforms under the pressure force of the fingers grip. Sometimes if the grasping position is not optimal, it can happen that it deforms in a weird way and the grip drops down it while the robot is moving.	Deformable
18	FIngers		YES	Even if the weight of the component is high, its trapezoid shape allows the fingers grip, in the central position, to have an excellent grip.	Geometrical shape - medium size
19	Fingers		YES	This component is not often optimally oriented for the grip, but due to its low weight and small size, fingers grip is able to grasp it because of the joint in the middle of finger.	Small size - low weight
20	FIngers		YES	The component weight is medium, so even though the walls in central position, on which it can grasped are smooth, the grip fingers have not difficulty in holding the component when the robot is moving until it is released.	Medium weight - geometrical shape - medium size
21	Fingers		YES	This component has a medium size and a very low weight so, if the grip has the possibility to grasp the component along the thickness there is no difficulty, while if the component is lying on the extended face the grip has only a few millimeters on which to grasp it and it could be happened that the component drop down.	Low weight - geometrical shape - medium size
22	FIngers		YES	Due to the large size of this component, the grip can't grasp it externally, but since the component is hollow and its weight is medium, a finger can get inside the cavity, grasping it on the thickness.	Hollowness
23	Fingers		YES	The size of this component is large, but because of the fact that it is hollow, the fingers grip can grasp at one of the 2 extremities.	Low weight - hollowness

Table 11 - Results of grasping test by fingers grip (continued)

Case	Type of grip	Picture	Picking success	Motivation	Crucial physical characteristic
24	Fingers		YES	Even if the size of this component is critical for fingers grip, due to the width of the component on its shorter side is just a few millimetres less than the maximum grip opening, the fingers grip can still carefully grasp it.	Geometrical shape - medium weight
25	Fingers		YES	This component has a non-geometrical shape, so most of the time it will be lying down and the grip have to grasp it along its thickness that is very thin. Nevertheless the fingers grip is suitable for this type of grip.	Small size - low weight
26	Fingers		YES	Even if the shape of this component is hard to recognize by the robot because it's very articuled, the fingers grip can grasp it very carefully, choosing the right position, also due to its low weight.	Medium size - low weight
27	Fingers		YES	This component has a cylindrical shape and small size and weight, reasons for that it's very easy to fingers grip to grasp it both laterally and axially.	Small size - low weight - geometrical shape
28	Fingers		YES	This component has a cylindrical shape with medium size. So, the fingers grip can easily grasp this component by placing its fingers externally or inserting one into the inner cavity.The fact that it is made of rubber does not cause any problems as it remains very stiff.	Medium size - low weight - geometrical shape
29	Fingers		YES	This component has a prism shape with medium size and low weight. These caracteristics allows the fingers grip to easily grasp it on the thickness.	Low weight - geometrical shape
30	Fingers		NO	This component has a very big size and not having a dimension small than the others, in the case if the component is oriented with its convex side, for the fingers grip is impossible to grasp it because the component size is bigger than the maximum opening of the grip.	Big size

As can be seen from the Table 8, Table 9, Table 10 the fingers grip fits well on many components of various shapes and sizes. However, one case where the fingers grip grasping was not successful was when the component had a larger size than the maximum grip opening and there was no possibility to enter with a finger of the grip into a cavity of the component, because it was convexly oriented to the grip (case 30). Another case of failure (case 16) was when the weight of the component was excessive and the walls of the component, being made of steel, were slippery, so the grip clamps could not hold the component firmly lifted off the ground. Finally, the case in which the component, being made of rubber, when the grip position was not optimal, it happened that the component deformed in a strange way, making the component drop down (case 17). From the latter case, we can therefore indicate that the fingers grip is not always suitable for gripping flexible components. In all other cases the fingers grip has been successful both for small, medium and large components, both for solid and hollow components and for components with geometrical and non-geometrical shapes. In all cases where the success of the picking is negative, this component should be assigned to the operator, who with his high sense-motor skills will be able to grasp the components.

4.2.3 - Summary of the main results related to research question 2

In this sub-section there is a summary useful for understand the parameter "Easiness of grasping", derived from the analysis of the experiments presented in the sub-section 4.2.2.

A component classified as "**easy grasping**" has the following characteristics:

- parallelepiped shape and medium size, with the thickness comparable with the other two dimensions;
- hollow cylindrical shape, so that, for example, one clamp of the fingers grip can enter the cavity so that the grip is able to grasp the component on its edge;
- can be grasped in different positions, without compromising the outcome of the grip;
- wide planar surface;
- low weight;
- low fragility;
- high stiffness;

A component classified as "**medium difficult grasping**" has the following characteristics:

- small size;
- cylindrical shape with medium radius of curvature;
- low thickness compared to other dimensions;
- non-geometrical shape without and medium weight;
- low fragility;
- high stiffness;

A component classified as "**high difficult grasping**" has the following characteristics:

- very small size or big size;

- non-geometrical shape together with high weight;
- cylindrical shape with small radius of curvature;
- small planar surface;
- high fragility;
- low stiffness;
- high weight and highly smooth surface;

4.3 - The influence of contextual factors on the time-efficiency

Research question 3 concern the influence of the contextual factors on the time-efficiency performance and is restated here for reference:

Research question 3:
How does contextual factors influence the time-efficiency in hybrid kits preparation?

The aim of this section is to evaluate the influence of the contextual factors on time-efficiency. In particular three central aspects of kits preparation are "**number of components picked per SKU**", the "**component size**", the "**easiness to grasping component**".

In these experiments, the time-efficiency is evaluated by measuring the time needed to complete one kit, and then the average time to kit a single component has been calculated, using this formula:

$$Average\ time\ for\ kit\ a\ single\ component = \frac{Total\ time\ to\ prepare\ a\ kit}{Number\ of\ components\ per\ kit}$$

The Table 12 shows the various settings used in the different cases examined in the experiments about the research question 3.

Table 12 - Cases list about the experiments of Section 4.3.

Case	Category	
A	Number of components per SKU	2 components per SKU
B	Number of components per SKU	1 component per SKU
C	Component size	Small Size
D	Component size	Medium Size
E	Component size	Big Size
F	Easiness of grasping	Easy Grasping
G	Easiness of grasping	Medium Difficult Grasping
H	Easiness of grasping	High Difficult Grasping

4.3.1 - Number of components per SKU

This section provides the results of the tests concerning the influence of the "number of components per SKU" on time-efficiency, shown in Table 13.

Table 13 - Results of the experiment: "How the number of components per SKU influences the time-efficiency".

Case	Category	Average time to KIT a single component [s]	Standard Deviation [s]	Average time to PICK a single component [s]	Standard Deviation [s]	Average time to PLACE a single component [s]	Standard Deviation [s]
A	2 components per SKU	14,13	0,54	1,90	0,14	2,36	0,34
B	1 component per SKU	15,06	0,61	2,30	0,16	2,43	0,20

Analyzing the data about the experiments on the "number of components per SKU" it can be noticed that the average time per kit a single component is slightly lower in the case A. This can be explained by the fact that if a kit contained more components of the same SKU, if their shape allows it, the robot's grip can pick two components at a time, almost halving the time it takes to pick that component. However, the action of taking two components at once means more time for grasping the components, as the action requires more precision than the picking of a single component. For these reasons the average time per kit a component in the case A is about 6% less than in the case B.

The standard deviation (6 tests) relative to the kitting time is considerable, mainly due to the high variability of the placing activity, as the component needs a different time to be placed in the kit package, depending on the presence or absence of other components already placed in the kit package that interfere with the placement of the component in question. In addition, the variability related to the travel time has to be considered. It depends mainly on the position that the component takes in the storage rack.

In conclusion, it can be said that the number of components per SKU doesn't influence time-efficiency significantly. More evident results could be obtained with an effective collaboration between the operator and the robot, where in the case A, the operator has the possibility to grasp more components of the same SKU at a time.

4.3.2 - Component size

This section provides the results of the tests concerning the influence of the "component size" on time-efficiency, shown in Table 14.

Table 14 - Results of the experiment: "How the component size influences the time-efficiency".

Case	Category	Average time to KIT a single component [s]	Standard Deviation [s]	Average time to PICK a single component [s]	Standard Deviation [s]	Average time to PLACE a single component [s]	Standard Deviation [s]
C	Small Size	13,01	0,73	2,37	0,17	2,41	0,09
D	Medium Size	17,25	0,20	3,01	0,21	3,57	0,19
E	Big Size	18,91	0,18	4,00	0,18	3,77	0,15

Analyzing the data about the experiments on the "Component size", it can be seen that the small components (case C) have recorded a lower average time to kit a component mainly because, in the case in which the kit composition includes more than one components per SKU, they can be grasped in pairs from the same grip and also because, given the small size of the components, it is not necessary to pay too much attention to their orientation in the kit package. The bigger components (case E) have the longest average time both considering the preparation of the whole kit and considering only the picking action. This is due to the fact that the fingers-grip, while approaching the

component, must slow down to be able to position itself correctly with extreme precision in proximity of the component, because the gap between the maximum grip opening and the component can be of the order of a few mm. Moreover, the time to position the component in the kit package is also the highest, due to the component has dimensions comparable to the dimensions of the kit package, the robot must proceed with caution in positioning the component in the kit package, choosing the right orientation.
In conclusion, it can be said that the component size greatly influences the kits preparation time, because they usually have a low weight as well and therefore don't compromise the solidity of the robot's grip. In addition, the small size allows the fingers grip to grasp the component externally whatever its shape.

4.3.3 - Easiness of grasping

This section provides the results of the tests concerning the influence of the "easiness of grasping" on time-efficiency, shown in Table 15.

Table 15 - Results of the experiment: "How the easiness of grasping influences the time-efficiency".

Case	Category	Average time to KIT a single component [s]	Standard Deviation [s]	Average time to PICK a single component [s]	Standard Deviation [s]	Average time to PLACE a single component [s]	Standard Deviation [s]
F	Easy Grasping	16,61	0,23	2,80	0,10	2,63	0,12
G	Medium Difficult Grasping	18,67	0,26	3,97	0,10	3,57	0,06
H	High Difficult Grasping	19,12	0,37	4,55	0,18	3,77	0,22

With regard to the easiness of grasping, it can be said that, as expected, the case F shows a picking time that is 29% less than components present in the case G and 38% less than components in the case H. Moreover, also the placing time, in the case F, is 26% lower than case G and 30% lower than case H. Overall, the average time per component in the kitting action is lower in the case F than the others two cases: case G and case H.
Considering the gaussian distribution of the experimental data, it is possible to distinguish 3 classes of times, centered in the average value to which is added/cut a share equal to about 2 times the standard deviation, to have a confidence interval as 95%. In particular, observing only the picking activity, the class relate respectively to the case F, case G and case H has an average time as it can be seen in the Figure 16.

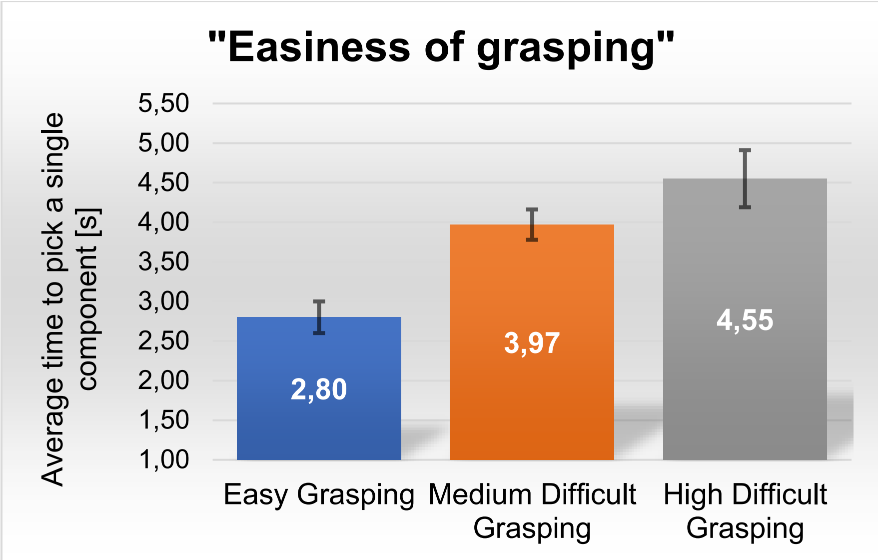


Fig. 16 - Average time and Interval of variability of the time to pick a single component, considering different grades of the factor: "Easiness of grasping"

The reason why the picking time in the case F is lower is due to the fact that the grip can approach the object quickly without giving too much attention to the position and orientation of the object, as it is possible to grasp it in more points.

In conclusion, it can be noted that the easiness of grasping greatly influences the time-efficiency.

4.4 - Comparison between different types of grip

Table 16 shows the two settings used in the experiment that involves comparing the two type of grip.

Table 16 - Cases list about the experiments of Section 5.4.

Case	Category	
I	Comparison between different types of grips	Fingers
L		Vacuum

4.4.1 - Fingers grip compare to Vacuum grip

This section provides the results of the tests concerning the comparison between fingers grip and vacuum grip picking components suitable for both the grips, shown in the current Table 17.

Table 17 - Results of experiment: "Comparison between fingers grip and vacuum grip".

Case	Category	Average time to KIT a single component [s]	Standard Deviation [s]	Average time to PICK a single component [s]	Standard Deviation [s]	Average time to PLACE a single component [s]	Standard Deviation [s]
I	Fingers	18,40	0,65	3,40	0,25	3,48	0,28
L	Vacuum	14,20	0,27	1,93	0,10	2,37	0,20

Comparing the two types of grips, making them grasp components suitable for both, you can see that the vacuum grip (case L) has a very advantageous kitting time compared to fingers grip (case I). More specifically, the vacuum grip has a kitting time 23% lower than the fingers grip. This time advantage is mainly due to the vacuum grip picking time, which is 43% lower than the fingers grip. Furthermore, also the placing time has contributed to generate this gap between the two types of grip, in fact the case L has a placing time 32% lower than the case I.

The reason why in the case L the picking time is 43% lower the in the case I, is mainly that in the case I the grip must adjust its opening according to the size of the component, and adjust the speed by increasing the accuracy especially if these are comparable with the maximum grip opening. The fingers grip, on the other hand, adapts to almost any shape a component may have and is therefore much more flexible than the vacuum grip, which requires that the surface of the component to be taken respects well-defined constraints, otherwise the grip fails.

Finally, it can be deduced that, for the components suitable for both types of grip, vacuum grip is more performing than fingers grip.

4.5 - Mathematical model of the cycle-time calculation

In addition to the work done, a model for estimating the time needed to complete a batch of kits has also been developed, inspired by the model proposed by (Boudella *et al.*, 2018). For further research, by assigning the values of the variables involved, based on the design and the context in which the experiments will be carried out, it is possible to calculate the average cycle time per kit for a single component, and then compare this result with the experimental one. It must be underline that this section doesn't have an experimental counterpart but is simply based on literature and personal considerations.

The aim of the model is to find the optimal assignment of SKUs between the operator and the robot that minimizes the total time needed to prepare a batch of kits. Alternatively, having already defined at the beginning the components to be assigned to the robot and the others to the operator, the model results in an estimate of the time needed for the preparation of a number of kits.

The model evaluated the cycle time CT^R and CT^O respectively for the robot and the operator, by summing of elementary kitting operations performed during a representative preparation cycle, over a reference time period. This time period is considered to be representative of average demand pertaining to the different models of EPs to assemble. Indeed, with each EP to produce is associated with a picking list that gives all SKUs needed and, for each SKU, the number of components to pick. Based on the picking lists both SKUs usage frequency and average number of components are computed:

- **Usage frequency "τ_i"** of SKU i represent the percentage of EPs in the reference period time that uses this SKU.
- **Average number of components "n_i"** to pick for SKU i is given by summing the BOM (Bill Of Material) coefficients for EPs produced in the reference period that use this SKU and dividing the result by the number of EPs.

The goal is to assign SKUs minimising the maximum cycle time between robot and operator. In other words, the aim is to achieve the cycle time of the operator equal to the cycle time of the robot, thus avoiding waiting times for one of the two resources. In this discussion only two resources are considered: one robot and one operator work in different areas of the same production cell, as it can be seen in the Section 2.6. The working shift of the robot is considered 24 hours, while the operator works for three shifts of eight hours each. The model's goal is represented in the following formula:

$$\textbf{Minimise maximum } (CT^R, CT^O)$$

Notations used in the model are given below:

- i: SKU index (i = 1 … C);
- C: the total number of SKUs considered in the hybrid kitting system;

- x_i: the binary decision variable indicating whether SKU i is assigned to the robot or the operator: "$x_i = 1$" if SKU is assigned to the robot; "$x_i = 0$" if SKU is assigned to the operator;
- BS (Batch Size): number of EPs prepared simultaneously;
- "R" and "O" refer respectively to the robot and the operator;

4.5.1 - Modelling the robot cycle time

The robot cycle time CT^R to prepare a kit of components associated with a batch of BS EPs is given by:

$$CT^R = T^R_{pick} + T^R_{place} + T^R_{vision} + T^R_{tool} + T^R_{trav} + T^R_{pack_{rem}} + T^R_{bin\_rem}$$

- T^R_{pick}: total pick time;
- T^R_{place} : total place time;
- T^R_{vision}: total image acquisition time of the storage bins content;
- T^R_{trav} : total travel time;
- T^R_{tool} : total time to change the grip before the operation of picking components, evacuating packaging items;
- $T^R_{pack\_rem}$: total time to remove inner packaging items;
- $T^R_{bin\_rem}$: total time to return empty bins;

Pick time.

This represent the time associated with picking all components required by BS EPs.

$$T^R_{pick} = \sum_{i=1}^{i=C}[x_i * (1 + \pi_i) * T^R_{i\_pick} * BS * \tau_i * n_i]$$

Where:

- $T^R_{i\_pick}$: the time needed for the robot to pick a single component of SKU i;
- π_i : proportion of failed picks associated with each SKU i (it represents the ability of the robot properly to pick components at the first attempt, obtained from field picking tests).
- $BS * \tau_i * n_i$: number of components to pick;

Place time.

This represent the time associated to place all components required by BS EPs into the kit packages.

$$T^R_{place} = \sum_{i=1}^{i=C}[x_i * (1 + \pi_i) * T^R_{i\_place} * BS * \tau_i * n_i]$$

Where:

- $T^R_{i\_place}$: the time needed for the robot to place a single component of SKU i into a kit package;

Image acquisition time.

This consists of taking a picture of the storage bin's content so that the robot can identify and propose relevant components to pick. It is given by:

$$T^R_{vision} = \sum_{i=1}^{i=C}[x_i * (\pi_i + (1 - p)) * T^R_{img} * BS * \tau_i * n_i]$$

Where:

- T^R_{img}: the time needed for a single image acquisition and analysis;
- p: part of image acquisition executed as a background task in a hidden time;
- $BS * \tau_i * n_i$: number of images acquisitions;

Travel time.

This is the total time needed for the robot to move along the aisle to pick all components required for the preparation of BS EPs and is given by:

$$T^R_{trav} = \sum_{i=1}^{i=C}\{x_i * [\frac{1}{v_R} * \frac{2*(B_i+S^R)}{N^R_{levels}*F^R} * BS + BS * \tau_i * T^R_s]\}$$

Where:

- v_R: the robot velocity;
- B_i: the size of bins contained SKU i components;
- S^R: the spacing between two successive bins;
- N^R_{levels}: the number of levels of storage racks in the robotic kitting system;
- F^R: the number of facades, that correspond to the number of pick sides from which the robot picks components;
- 2: is to consider to travel to go back at the starting point;

- T_s^R: the time needed to stop in front of the storage locations of SKU i;

Tool changing time.

This refers to the operation of changing the grasping tool:

$$T_{tool}^R = \sum_{i=1}^{i=C}\{x_i * [T_{tool\_chg}^R * (1 - P_{tool}) * BS * \tau_i * \pi_{tool\_chg} + (BS * \tau_i * n_i) * [T_{tool\_chg}^R * (1 - P_{tool}) * \frac{D_i}{P_i} + T_{tool\_chg\_bin}^R]\}$$

Where:

- $T_{tool\_chg}^R$: technological time needed for a single tool change before picking a component or a packaging item;
- $T_{tool\_chg\_bin}^R$: the technological time needed to perform a single tool change before removing an empty bin.
- P_{tool}: the part of the technological time executed in "hidden time". This value is unique whatever the need for a tool change;
- π_{tool_chg}: proportion of SKUs in a preparation cycle that requires a tool change (which also corresponds to the number of tool changes during a cycle);
- D_i: number of interlayer sheets, dividers per storage bin (full bin);
- P_i: number of components of SKU i per storage bin (full bin);

Time to remove inner packaging items.

This is the total time needed to remove packaging items (interlayers sheets and dividers) to reach components in a bin:

$$T_{pack\_rem}^R = \sum_{i=1}^{i=C}\{x_i * (1 + \pi_{pack}) * D_i * T_D^R * \frac{BS * \tau_i * n_i}{P_i}\}$$

Where:

- π_{pack}: the picking failure rate associated with removing packaging items;
- T_D^R: time to pick and place, into the apposite container, one interlayer, divider;

Time to return empty bins.

This refers to the operation of removing bins from their storage locations to be refilled by suppliers:

$$T^R_{bin\_rem} = [T^R_B * (1 + \pi_B) + T^R_{Bm} + 2 * T^R_s] * \sum_{i=1}^{i=C}[x_i * \frac{BS*\tau_i*n_i}{P_i}]$$

Where:

- T^R_B: the time required for the robot to remove a bin from its storage location and place it on the evacuation ramp.
- π_B: proportion of failed picks at the first attempt;
- T^R_{Bm}: time required to move a bin from its location to evacuation ramp. Is given by the travelled distance divided by the robot velocity, as in:

$$T^R_{Bm} = \frac{travelled\ distance\ to\ remove\ a\ bin}{v_R}$$

- T^R_s: include the first stop when the robot removes the bin and the second stop in front of the evacuation ramp. The stopping time when going back to the bin's location to pick a component has already been integrated into the travel time.
- $\sum_{i=1}^{i=C} x_i \frac{BS*\tau_i n_i}{P_i}$: gives the average number of empty bins removed during the preparation of BS EPs.

Robotic kitting assumptions

Pick and place

- The robot picks a single component at a time;
- Since components are stored in small bins, picking times are the same for all components in a bin;
- Time needed to rotate in order to place components into a kit package is included in place movement;
- An average picking failure rate is considered;

Image acquisition

- Image acquisition is done before each picked component. But since the experiments will be performed by the robot without the vision system, we can estimate an interval of time dedicated to the acquisition and revision of images, constant for all SKUs;

Travel

- The robotic kitting area is considered with one or two facades. The number of facades corresponds to the number of picking sides,

- After picking each component, the robot returns to the starting point, where it should place component in the kit package;
- A time to stop in front of the bins is considered;
- Bins are introduced in the storage racks to have their width on the robot's path;

Tool changing

- The robot adapts the tool for each item to pick (components, packaging items);
- A tool change is not necessarily carried out for each component to pick. Successive SKUs in the picking list can be picked with the same tool;
- A single tool change requires the same amount of time for components and packaging items;
- A tool change may be executed as a background task;
- The tool holder is connected to the base of the robotic arm. No travel time is needed to perform a tool change.

Remove inner packaging items

- The robot is able to pick interlayer sheets and dividers;
- An average picking failure rate is considered for both items;
- Items are dropped directly into an dedicated container with no travel time considered;
- The average number of packaging items calculated by considering that components consumed during the reference time period, are contained in full bins.

Return back empty bins

- The robot consumes full bins during the reference period;
- The robot may fail at retrieving empty bins at the first attempt;
- Only one evacuation ramp by all aisle.
- The time considered for picking an empty bin remains unchanged no matter the type of bin.

4.5.2 - Modelling the operator cycle time

The operator cycle time CT^{O} to prepare a kit of components associated with a batch of BS EPs is given by:

$$CT^{O} = T^{O}_{load} + T^{O}_{pick} + T^{O}_{place} + T^{O}_{trav} + T^{O}_{pack\_rem} + T^{O}_{bin\_rem} + T^{O}_{unload}$$

- T^{O}_{load}: total time to load empty packages on the kitting cart when starting the manual preparation;
- T^{R}_{pick}: total pick time;
- T^{R}_{place} : total place time;
- T^{R}_{trav} : total travel time;
- $T^{R}_{pack\_rem}$: total time to remove inner packaging items;
- $T^{O}_{bin\_rem}$: total time to return empty bins;
- T^{O}_{unlaod}: total time to unload filled boxes from kitting cart;

Time to load empty packages.

The average total time to load empty packages on the cart by operator is given by:

$$T^{O}_{load} = (BS * T_{kb} + T^{O}_{s}) * [K + \pi_{rich\_EP} * (K_{max} - K)]$$

Where:

- T_{kb}: the time required for the operator to handle one package;
- T^{O}_{s}: the time needed to the operator to stop in front of storage location;
- K: the minimum number of packages to prepare per EP;
- π_{rich_EP}: the proportion of rich EPs over the reference period;
- K_{max}: the maximum number of packages per EP;
- $BS * [K + \pi_{rich\_EP} * (K_{max} - K)]$: the average number of packages that operator loads on the kitting cart, for each preparation cycle;

Pick time.

This represent the time associated with picking all components required by BS EPs.

$$T^{O}_{pick} = \sum_{i=1}^{i=C}[(1 - x_i) * T^{O}_{i\_pick} * \frac{BS*\tau_i*n_i}{\vartheta_i}]$$

Where:

- $T^{O}_{i\_pick}$: the time needed for the operator to pick a single component of SKU i;
- $BS * \tau_i * n_i$: number of components to pick;
- ϑ_i: the number of components the operator picks simultaneously. This value corresponding to the minimum between the number of components of SKU i needed "$BS * \tau_i * n_i$" and "a_i" the maximum (theoretical) number of components the operator can pick simultaneously.

$$\vartheta_i = min\ (BS * \tau_i * n_i; a_i)$$

- The value of "a_i" and "$T^{O}_{i\_pick}$" depend on components size of SKU i.

Place time.

This represent the time associated to place all components required by BS EPs into the kit packages.

$$T^{O}_{pick} = \sum_{i=1}^{i=C}[(1 - x_i) * T^{O}_{i\_place} * \frac{BS*\tau_i*n_i}{\vartheta_i}]$$

Where:

- $T^{O}_{i\_place}$: the time needed for the operator to place a single component of SKU i into a kit package;

Travel time.

This is the total time needed for the operator to move along the aisle to pick all components required for a set of BS EPs.

$$T^{O}_{trav} = \sum_{i=1}^{i=C}(1 - x_i) * \{[K + \pi_{rich_{EP}} * (K_{max} - K)] * [\frac{1}{v_O} * \frac{2*(B_i+S^O)}{N^{O}_{levels}*F^O} + \tau_i * T^{O}_{s}]\}$$

Where:

- v_O: the operator velocity;
- B_i: the size of bins contained SKU i components;
- S^O: the spacing between two successive bins;

- N_{levels}^{O}: the number of levels of storage racks in the manual kitting system;
- F^{O}: the number of facades, that correspond to the number of pick sides from which the operator picks components;
- 2: is to consider to travel to go back at the starting point;
- T_{s}^{O}: the time needed to stop in front of the storage locations of SKU i;
- $\left[K + \pi_{rich_{EP}} * (K_{max} - K)\right] * \frac{2}{F^{O}}$: the total number of roundtrips;
- $\sum_{i=1}^{i=C}(1 - x_i) * \frac{(B_i + S^{O})}{N_{levels}^{O}}$: total picking facades length;

Time to remove inner packaging items.

This is the total time needed to remove packaging items (interlayers sheets, dividers and plastic bag) to reach components in a bin:

$$T_{pack\_rem}^{O} = \sum_{i=1}^{i=C}\{(1 - x_i) * (D_i * T_D^{O} + Pb_i * T_{Pb}^{O}) * \frac{BS * \tau_i * n_i}{P_i}\}$$

Where:

- D_i: number of interlayer sheets, dividers per storage bin (full bin);
- T_D^{O}: time to pick and place, into the apposite container, an interlayer, divider;
- Pb_i: the number of plastic bags;
- T_{Pb}^{O}: time to pick and place, into the apposite container a plastic bag;
- P_i: number of components of SKU i per storage bin (full bin);
- $\sum_{i=1}^{i=C}\{(1 - x_i) * (D_i * T_D^{O} + Pb_i * T_{Pb}^{O})\}$: the time to remove all items in a bin;
- $\sum_{i=1}^{i=C}\{(1 - x_i) * \frac{BS * \tau_i * n_i}{P_i}\}$: the number of bins consume during a preparation cycle;

Time to return empty bins.

As for a robot, the operator evacuates depleted bins:

$$T_{bin\_rem}^{O} = \sum_{i=1}^{i=C}\{(1 - x_i) * T_B^{O} * \frac{BS * \tau_i * n_i}{P_i}\}$$

Where:

- T_B^{O}: time needed by the operator to remove any empty bins from their storage location and place them on the evacuation ramp;

Time to unload full packages.

This corresponds to the time needed to unload, from the kitting cart, full packages and place them in a stock area.

$$T_{unload}^{O} = (BS * T_{kb} + T_{s}^{O}) * [K + \pi_{rich\_EP} * (K_{max} - K)]$$

Where:

- T_{kb}: the time required to the operator for handling a package;

Human kitting assumptions

Load empty packages

- Some models of EPs require a higher diversity of SKUs thus, more boxes to hold picked components;
- A time to stop in front of the gravity flow lines where empty boxes are accumulated, is considered;

Pick and place

- The operator can pick multiple components simultaneously;
- Time required to pick/place components depends on the size of SKUs and the number of picked components;
- No picking errors considered because of the use of a pick-to-light system;

Travel

- The manual kitting area is considered with one or two facades. The number of facades corresponds to the number of picking sides;
- After picking each component, the operator returns to the starting point, where it should place component in the kit package;
- The operator completes robot preparation with the remaining components;
- A time to stop in front of the bins is considered;
- Bins are introduced in the storage racks to have their width on the robot's path;

Remove inner packaging items

- The operator can remove all packaging items: dividers, interlayer sheets, plastic bags;
- There are plenty of waste bins to throw the different packaging items so that operator has no need to travel;

- The average number of packaging items removed during a preparation cycle is calculated assuming that components, consuming during the reference time period, are contained in full bins.

Return back empty bins

- The operator consumes full bins during the reference time period;
- No need to travel along the aisle to evacuate empty bins. All lanes of rack's bottom level can receive depleted bins.
- The time considered for picking an empty bin remains unchanged no matter the type of bin.

Unload full boxes

- As for the operation of loading boxes, we consider an average number of boxes for each EP;
- Time to stop in front of the gravity flow lane, where filled boxed are placed, is considered;

4.6 - Overview of the main results

The answer to research question 1 improves the understanding of how the design of the kitting system influence the time-efficiency performance. From the previous literature analysis, it is clear that the five variables on which attention must be focused in order to be time-efficient are:

- Layout: high picking density of the hybrid kits preparation area;
- Policy: large batch size;
- Picking information: pick-by-light information system;
- Equipment: moving kit cart;
- Work organisation: have a balance between resources in terms of quantity of work.

The answer to research question 2 improves the understanding of how to organize the resources of the kitting area according to the characteristics of the components. In particular, includes a model of categorisation of the components based on their physical characteristics to be able to understand which components are suitable to the robotic kitting area and which one are suitable to the manual kitting area. It is logical to think how the operator can be entrusted with all those components not suitable for the robotic area. This is confirmed by the fact that the operator is equipped with advanced psycho-motor skills that allow him to adapt to the grip of any component entrusted to him. Furthermore, from the analysis of the experimental results focused on the robotic kitting area, it has been possible to denote that the fingers grip adapts itself to the major part of components with complex shapes, different weights and from small to medium sizes, while the vacuum grip needs more restrictive constraints on the characteristics of components to be grasped, for example, large planar surface, medium-big size and wide radius of curvature.

The answer to research question 3 improves the understanding of how the contextual factors influence the time-efficiency, by having several numbers of tests in which 3 different contextual factors are analysed. The analysis of the results clearly shows that the factors "Component Size" and “Easiness of grasping” have a significant influence on time-efficiency, while the “Number of components per SKU” factor doesn’t have a great influence on the time-efficiency. In addition, the analysis of the comparison between the two grip types showed that the vacuum grip, for the components suitable for both grips, is more performing than the fingers grip in terms of time-efficiency. However, fingers grip has a better ability to adapt to the physical characteristics of the components, being able to grasp complex components.

5. Conclusion

This work aims to study in deep kits preparation for assembly line system with hybrid configurations, i.e., where there is a collaboration between picking operators and collaborative robots to prepare kits to be delivered to the assembly line. The industrial relevance of studying kits preparation system from the increasing use of kits preparation in industry, which is the result of the need to better manage more component variants in production system. The use of collaborative robots in the kits preparation as well as slightly reducing the time needed to prepare kits, offering a more stable outcome than kits preparation performed manually. Furthermore, cobots application supporting kit quality by removing the risk of human errors. Finally, collaborative systems have an ergonomic benefit reducing operator fatigue by relieving operators from the toughest tasks. From this point of view, they are increasingly popular because the average retirement age is rising and the workforce in European industries is getting older and older.

Experience and guidelines for how to design these processes have been lacking, especially if the collaboration between robots and operators is taken into account, and from a theoretical viewpoint, knowledge has been lacking on relationship between the hybrid kits preparation design and a specific performance.

To complement this lacking knowledge, three research questions were formulated respectively focused on: the influence of the design variables on time-efficiency of the hybrid kitting system, the categorisation of components based on their physical characteristic, the influence of the contextual factors on time-efficiency of the hybrid kitting system.

The answers of each research question make an important contribution to expanding knowledge about how design and contextual variables affect the time-efficiency performance of the hybrid kitting system. Previous literature about the hybrid kitting system is really scarce, saving the paper of Boudella *et al.* (2018). In addition, a model for the classification of the components according to their physical characteristics has been formulated. This kind of model and subsequent experimental validation is completely new in the literature.

These study conclusions can help industrial manager to provide answer to questions like: "If I want to optimize kits preparation activities in terms of time-efficiency performance, how should I design my kitting process?" or "Given a certain production order that includes components with specific characteristics, which components do I assign to the robot and which to the operator?".

The study related to the influence of design variables on time-efficiency was mainly based on an analysis of the previous literature, exploring a more generic field that included order picking and material handling. Results showing the design variables that have most influenced the performance of the hybrid kitting system in terms of time-efficiency, have made a significant contribution on how take these variables into account when designing a new hybrid kitting area in un industrial context.

The study on the categorization of the components was based both on an analysis of the previous literature and experimental evidences. The categorization model, supported by the experimental evidence, offers considerable support in the assignment of components between the operator and the robot in the hybrid kitting area. Going more specifically, it is possible to predict the most suitable grip that the robot will have to use to grip a certain category of components.

The study related to the research question 3 was developed by means of experiments aimed at analysing the influence of a specific contextual factors on the time-efficiency. The hybrid kitting system has been configurated and built up in the SII-lab in order to reproduce an industrial hybrid kitting system. The results obtained will bring a great contribution in extending the previous understanding of the relationship between contextual factors and time-efficiency. In addition, an analytical model that aims at optimal distribution of work between robot and operator is proposed. Furthermore, this model can be useful to estimate the time needed for the batch kits preparation by robot and operator. The modelling approach developed in this study can be used as a basis for analysing other configurations (e.g. two robots in the robotic kitting area, one for picking components, the other for placing them into kit packages, to reduce the recurrent operations of the operator).

A limitation of this approach is that the experiments where from the experimental data were retrieved, have been simplified to compare to the real industrial settings, and there may be other aspects not covered by the experiments that needs consideration with respect to implementation of the cobot-application. In addition, it should be noted that the experiments were carried out using a small-scale robot trying to simulate the performance of a collaborative robot used in an industrial context. The analysis of the hybrid kitting system did not take into account the activities carried out by the operator in terms of man-hour efficiency because they were widely extended in the previous literature (Hanson and Medbo, 2019). In fact, the focus of the experiments was to analyse the time-efficiency of the robot because it's engineeringly stimulating due to the lack of knowledge and the numerous variables that could be analysed.

Future research should explore how collaborative robots could support the kits preparation in other settings, for example in warehouse order picking considering longer travelling distances that affects the time-efficiency performance. Aside from time-efficiency, future research should also consider how collaborative robot applications affect other performance of kits preparation such as flexibility, quality, ergonomics and cost.

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Appendix A

In this appendix all the kit compositions necessary for the tests described in the section 3.3.2 are shown. All numbers related to the storage rack position referred to Figure 17.

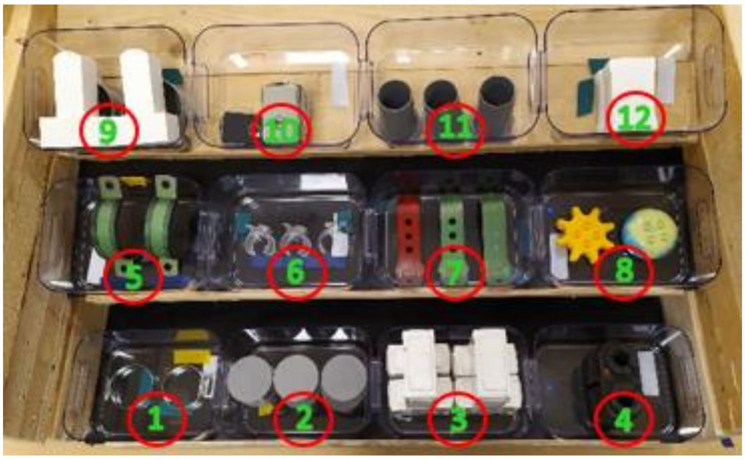

Fig. 17 - Composition scheme.

Contextual factor 1: Number of components picked per SKU

In the following section we will analyze how the contextual factor "Number of components per SKU" influences the performance "Time-efficiency". In particular we will test 2 configurations: the first one, where the content of the kit to be prepared, requires the presence of two components for each SKU, while the second configuration requires one component for each SKU. In all configurations, one kit is composed by 6 components. The kit composition related to the analyses of the sub-section of the contextual factors 1 is shown in the Figure 18.

Configuration type: 2 components per SKU						
Number of kit	Component position in the rack					
1	1	1	6	6	10	10
2	9	9	3	3	8	8
3	11	11	10	10	8	8
4	4	4	9	9	10	10
5	5	5	8	8	1	1
6	7	7	3	3	2	2

Configuration type: 1 component per SKU						
Number of kit	Component position in the rack					
1	5	2	9	6	10	4
2	7	9	10	3	8	11
3	1	12	10	5	8	6
4	3	8	5	11	12	1
5	4	7	3	2	8	6
6	9	5	6	8	11	3

Fig. 18 - Contextual factor 1: component's position in the rack.

Contextual factor 2: Component size

In the following section we will analyze how the contextual factor "Component size" influences the performance "Time-efficiency". In particular we will test 3 configurations: the first one includes small size components, the second one includes medium size components and the third one includes big size components.

The number of components present in one kit depends on the component size, because the maximum number of components that can be contained in a kit package depends on their size. In particular kit package contained 6 small-size components, 4 medium-size components and 3 big-size components. The kit composition related to the analyses of the sub-section of the contextual factors 2 is shown in the Figure 19, Figure 20, Figure 21, respectively.

Configuration type: Small size						
Number of kit	Component position in the rack					
1	6	6	6	2	2	10
2	10	10	8	8	1	1
3	6	6	3	3	3	3
4	3	7	5	5	4	1
5	7	8	8	11	2	4
6	3	7	2	6	6	10

Fig. 19 - Contextual factor 2: Small size component's position in the rack.

Configuration type: Medium size						
Number of kit	Component position in the rack					
1	4	11	9	2	/	/
2	5	10	1	7	/	/
3	6	3	12	8	/	/
4	3	7	5	1	/	/
5	12	8	11	2	/	/
6	6	10	4	3	/	/

Fig. 21 - Contextual factor 2: Medium size component's position in the rack.

Configuration type: Big size						
Number of kit	Component position in the rack					
1	5	2	12	/	/	/
2	6	1	9	/	/	/
3	7	4	3	/	/	/
4	4	12	2	/	/	/
5	6	5	9	/	/	/
6	3	7	1	/	/	/

Fig. 20 - Contextual factor 2: Big size component's position in the rack.

Contextual factor 3: Easiness to grasping

In the following section we will analyze how the contextual factor "Easiness to grasping" influences the performance "Time-efficiency". In particular we will test 3 configurations: the first one includes “Easy grasping components”, the second one includes “Medium difficult grasping components” and the third one includes “High difficult grasping components”.

The kit composition related to the analyses of the sub-section of the contextual factors 3 is shown in the Figure 22, Figure 23, Figure 24, respectively.

Configuration type: Easy grasping				
Number of kit	Component position in the rack			
1	1	4	8	2
2	2	7	3	6
3	1	7	5	4
4	1	4	2	8
5	6	2	3	7
6	4	5	1	7

Fig. 22 - Contextual factor 3: Easy grasping component’s position in the rack.

Configuration type: Medium difficult grasping				
Number of kit	Component position in the rack			
1	8	3	5	2
2	1	7	4	6
3	6	5	7	1
4	3	6	2	8
5	1	5	4	7
6	8	5	6	4

Fig. 23 - Contextual factor 3: Medium difficult grasping component’s position in the rack.

Configuration type: High difficult grasping				
Number of kit	Component position in the rack			
1	5	7	1	8
2	4	3	2	7
3	6	2	7	5
4	3	1	2	5
5	8	3	7	4
6	6	5	1	8

Fig. 24 - Contextual factor 3: High difficult grasping component’s position in the rack.

Comparison between fingers grip and vacuum grip

In the following section we will analyze the comparison in terms of time-efficiency between the fingers grip and the vacuum grip grasping the same SKUs suitable for both type of grip. The kit composition related to the analyses of the sub-section is shown in the Figure 25.

Configuration type: Fingers and vacuum grips				
Number of kit	Component position in the rack			
1	6	10	11	3
2	5	1	1	4
3	7	9	8	8
4	2	12	10	6
5	1	3	5	7
6	12	10	9	8
7	2	7	1	2
8	3	8	4	5
9	6	6	11	8

Fig. 25 - Comparison between grips: component's position in the rack.

Appendix B

In this Appendix are shown the data collection of all experiments related to the research question 3.

Table 18 - Data collection of the experiment regards the contextual factor 1: "Number of parts per SKU". In this table the "Average time" and the "Standard deviation" regard the Picking, Travelling and Placing task are shown respectively.

Exp	Kit "number"	Number of parts per kit	Time to pick	Time to travel	Time to place	Time to kit	Average time to KIT a single component	AV	S.D.	Average time to PICK a single component	AV	S.D.	Average time to PLACE a single component	AV	S.D.
2 parts per SKU	1	6	2,5	11,5	3,3	17,3	14,23	**14,13**	**0,54**	2,02	**1,90**	**0,14**	2,50	**2,36**	**0,34**
			2,3	12	3,1	17,4									
			2,5	11,5	3,2	17,2									
			2,5	11,8	2,6	16,9									
			2,3	11,5	2,8	16,6									
	2	6	2,8	11,9	3,5	18,2	13,30			1,97			2,38		
			2,3	10,5	2,8	15,6									
			2,4	10,4	2,9	15,7									
			2,1	10,4	2,6	15,1									
			2,2	10,5	2,5	15,2									
	3	6	2,2	11,3	3,2	16,7	13,87			1,97			2,25		
			2,5	11,7	2,6	16,8									
			2,6	11,9	2,8	17,3									
			2,2	11,8	2,5	16,5									
			2,3	11,2	2,4	15,9									
	4	6	1,5	10,3	3	14,8	13,97			1,65			2,40		
			1,6	10	3,2	14,8									
			1,8	9,6	1,8	13,2									
			2	9,7	2	13,7									
			1,3	9,8	2,1	13,2									
			1,7	10,1	2,3	14,1									
	5	6	2,4	9,6	2,5	14,5	14,58			1,82			2,83		
			2,3	10,2	2,7	15,2									
			1,5	10,1	2,8	14,4									
			1,6	9,8	2,9	14,3									
			1,5	9,9	3,1	14,5									
			1,6	10	3	14,6									
	6	6	2	9,9	2,4	14,3	14,80			1,97			1,80		
			2,3	9,9	2,1	14,3									
			2,3	10,2	1,9	14,4									
			2,1	10,7	2	14,8									
			2,5	10,5	2,4	15,4									
			2,6	10,6	2,4	15,6									

Table 19 - Data collection of the experiment regards the contextual factor 1: "Number of parts per SKU". In this table the "Average time" and the "Standard deviation" regard the Picking, Travelling and Placing task are shown respectively.

Exp	Kit "number"	Number of parts per kit	Time to pick	Time to travel	Time to place	Time to kit	Average time to KIT a single component	AV	S.D.	Average time to PICK a single component	AV	S.D.	Average time to PLACE a single component	AV	S.D.
1 part per SKU	11	6	2,4	10,9	3	16,3	16,05	**15,06**	**0,61**	2,50	**2,30**	**0,16**	2,65	**2,43**	**0,20**
			2,5	10,7	2,8	16									
			2,6	11,8	2,6	17									
			2,5	10,8	2,4	15,7									
			2,2	11,2	2,6	16									
			2,8	10	2,5	15,3									
	12	6	2,8	10,6	3,1	16,5	15,25			2,47			2,52		
			2,4	10,6	2,5	15,5									
			2,2	10,2	2,1	14,5									
			2,5	9,6	2,4	14,5									
			2	10,1	3	15,1									
			2,9	10,5	2	15,4									
	13	6	2,1	11,8	2,7	16,6	15,35			2,30			2,52		
			2,6	11,2	2,4	16,2									
			2,2	10,3	2,3	14,8									
			2,4	10,1	2,5	15									
			2	9,7	2,8	14,5									
			2,5	10,1	2,4	15									
	14	6	2,3	10,8	2,2	15,3	14,75			2,07			2,53		
			1,9	9,9	1,9	13,7									
			2,5	9,5	3	15									
			2	11,3	2,3	15,6									
			1,8	9,9	2,8	14,5									
			1,9	9,5	3	14,4									
	15	6	2	9,5	3	14,5	14,52			2,23			2,13		
			2,5	10,7	1,5	14,7									
			2,3	10,5	2,2	15									
			2,6	10,8	2,2	15,6									
			1,8	10	1,9	13,7									
			2,2	9,4	2	13,6									
	16	6	1,8	10,1	1,8	13,7	14,45			2,22			2,25		
			2,6	9,6	1,9	14,1									
			2,4	9,8	1,9	14,1									
			1,8	9,6	2,5	13,9									
			2,1	10,4	2,8	15,3									
			2,6	10,4	2,6	15,6									

Table 20 - Data collection of the experiment regards the contextual factor 2: "Component size". In this table the "Average time" and the "Standard deviation" regard the Picking, Travelling and Placing task are shown respectively.

Exp	Kit "number"	Number of parts per kit	Time to pick	Time to travel	Time to place	Time to kit	Average time to KIT a single component	AV	S.D.	Average time to PICK a single component	AV	S.D.	Average time to PLACE a single component	AV	S.D.
Small Size	1	6	3,8	11,7	3,6	19,1	12,38	**13,01**	**0,73**	2,50	**2,37**	**0,17**	2,30	**2,41**	**0,09**
			4	11,3	3,2	18,5									
			4,2	11,3	3,4	18,9									
			3	11,2	3,6	17,8									
	2	6	3,2	12,1	3,5	18,8	12,20			2,17			2,50		
			3,4	12,1	3,8	19,3									
			3,1	10,8	3,9	17,8									
			3,3	10,2	3,8	17,3									
	3	6	3,5	11,2	3,4	18,1	12,47			2,45			2,43		
			3,5	11,2	3,7	18,4									
			3,8	11,7	3,6	19,1									
			3,9	11,4	3,9	19,2									
	4	6	3,2	11,6	3,4	18,2	13,72			2,15			2,50		
			2,6	9,7	2,9	15,2									
			2,1	11	2,9	16									
			2,6	11,6	2,8	17									
			2,4	10,5	3	15,9									
	5	6	3,6	11,3	3,3	18,2	13,73			2,55			2,43		
			2,6	10,4	3,2	16,2									
			2,5	11,6	2,4	16,5									
			2,7	9,7	3,2	15,6									
			3,9	9,5	2,5	15,9									
	6	6	3,4	9,7	2,9	16	13,55			2,42			2,30		
			2,7	10,8	3,1	16,6									
			2,7	10,8	2,9	16,4									
			2,6	10,4	2,6	15,6									
			3,1	11,3	2,3	16,7									

Table 21 - Data collection of the experiment regards the contextual factor 2: "Component size". In this table the "Average time" and the "Standard deviation" regard the Picking, Travelling and Placing task are shown respectively.

Exp	Kit "number"	Number of parts per kit	Time to pick	Time to travel	Time to place	Time to kit	Average time to KIT a single component	AV	S.D.	Average time to PICK a single component	AV	S.D.	Average time to PLACE a single component	AV	S.D.
Medium Size	11	4	3,6	11,8	3,4	18,8	17,25	**17,25**	**0,20**	3,20	**3,01**	**0,21**	3,45	**3,57**	**0,19**
			2,7	10,2	3,3	16,2									
			3,1	10,9	3,7	17,7									
			3,4	9,5	3,4	16,3									
	12	4	3,1	10,6	4,1	17,8	17,45			3,25			3,78		
			3,2	10,8	3,5	17,5									
			3,8	9,7	3,7	17,2									
			2,9	10,6	3,8	17,3									
	13	4	2,6	11,8	3,5	17,9	17,50			2,95			3,65		
			2,4	10,8	3,9	17,1									
			3,5	9,7	3,6	16,8									
			3,3	11,3	3,6	18,2									
	14	4	3,6	10,9	3,2	17,7	17,03			3,10			3,25		
			2,9	11,2	3,1	17,2									
			2,5	10,1	3,5	16,1									
			3,4	10,5	3,2	17,1									
	15	4	2,7	11,6	3,7	18	17,23			2,88			3,60		
			2,7	9,8	3,4	15,9									
			3	11,3	3,3	17,6									
			3,1	10,3	4	17,4									
	16	4	2,6	10,8	4,1	17,5	17,05			2,70			3,70		
			2	10,8	3,9	16,7									
			2,7	10,3	3,2	16,2									
			3,5	10,7	3,6	17,8									

Table 22 - Data collection of the experiment regards the contextual factor 2: "Component size". In this table the "Average time" and the "Standard deviation" regard the Picking, Travelling and Placing task are shown respectively.

Exp	Kit "number"	Number of parts per kit	Time to pick	Time to travel	Time to place	Time to kit	Average time to KIT a single component	AV	S.D.	Average time to PICK a single component	AV	S.D.	Average time to PLACE a single component	AV	S.D.
Big Size	21	3	3,7	10,9	4,8	19,4	18,73	**18,91**	**0,18**	3,87	**4,00**	**0,18**	3,90	**3,77**	**0,15**
			4,2	11,2	3,2	18,6									
			3,7	10,8	3,7	18,2									
	22	3	4	11,1	3,7	18,8	19,23			3,97			3,77		
			4,3	12	3,4	19,7									
			3,6	11,4	4,2	19,2									
	23	3	3,8	10,5	3,7	18	18,83			4,27			3,97		
			4,4	10,4	4,4	19,2									
			4,6	10,9	3,8	19,3									
	24	3	4,4	10,7	3,5	18,6	18,87			4,17			3,57		
			3,8	12	3,3	19,1									
			4,3	10,7	3,9	18,9									
	25	3	4,5	12,2	3,5	20,2	18,80			3,83			3,63		
			3,8	10,3	3,6	17,7									
			3,2	11,5	3,8	18,5									
	26	3	4,5	10,5	3,5	18,5	18,97			3,90			3,80		
			3,5	11,3	4,2	19									
			3,7	12	3,7	19,4									

Table 23 - Data collection of the experiment regards the contextual factor 3: "Easiness of grasping". In this table the "Average time" and the "Standard deviation" regard the Picking, Travelling and Placing task are shown respectively.

Exp	Kit "number"	Number of parts per kit	Time to pick	Time to travel	Time to place	Time to kit	Average time to KIT a single component	AV	S.D.	Average time to PICK a single component	AV	S.D.	Average time to PLACE a single component	AV	S.D.
Easy Grasping	1	4	2,9	11,0	2,6	16,5	16,45	**16,61**	**0,23**	2,93	**2,80**	**0,10**	2,55	**2,63**	**0,12**
			2,7	10,5	2,4	15,6									
			3,1	11,5	2,5	17,1									
			3	10,9	2,7	16,6									
	2	4	3,2	11,2	2,6	17	16,88			2,90			2,65		
			2,5	11,6	2,7	16,8									
			2,9	11,2	2,8	16,9									
			3	11,3	2,5	16,8									
	3	4	2,8	10,7	2,6	16,1	16,25			2,68			2,65		
			3	10,5	2,7	16,2									
			2,3	11,6	2,9	16,8									
			2,6	10,9	2,4	15,9									
	4	4	2,7	11,8	2,4	16,9	16,55			2,73			2,45		
			2,9	11,4	2,2	16,5									
			2,8	11,3	2,4	16,5									
			2,5	11	2,8	16,3									
	5	4	2,5	11,3	2,7	16,5	16,75			2,75			2,65		
			3,1	11,5	2,6	17,2									
			2,8	11,2	2,4	16,4									
			2,6	11,4	2,9	16,9									
	6	4	3,1	11,2	2,5	16,8	16,78			2,83			2,83		
			2,7	11,4	2,7	16,8									
			2,8	11,3	2,9	17									
			2,7	10,6	3,2	16,5									

Table 24 - Data collection of the experiment regards the contextual factor 3: "Easiness of grasping". In this table the "Average time" and the "Standard deviation" regard the Picking, Travelling and Placing task are shown respectively.

Exp	Kit "number"	Number of parts per kit	Time to pick	Time to travel	Time to place	Time to kit	Average time to KIT a single component	AV	S.D.	Average time to PICK a single component	AV	S.D.	Average time to PLACE a single component	AV	S.D.
Medium Difficult Grasping	11	4	3,8	10,8	3,4	18	18,45	**18,67**	**0,26**	4,03	**3,97**	**0,10**	3,50	**3,57**	**0,06**
			4,6	11,3	3,5	19,4									
			3,6	10,7	3,3	17,6									
			4,1	10,9	3,8	18,8									
	12	4	4,3	10,7	3,6	18,6	18,98			4,00			3,63		
			4,4	11,4	4	19,8									
			3,5	12,1	3,5	19,1									
			3,8	11,2	3,4	18,4									
	13	4	3,8	11,4	3,5	18,7	18,50			4,03			3,50		
			3,4	11	3,9	18,3									
			4,4	10,3	3,3	18									
			4,5	11,2	3,3	19									
	14	4	4,3	11,5	3,54	19,34	18,66			3,98			3,64		
			3,7	11,2	3,8	18,7									
			4,3	10,9	3,2	18,4									
			3,6	10,6	4	18,2									
	15	4	4,5	11,4	3,6	19,5	19,00			4,00			3,60		
			3,5	12,3	3,5	19,3									
			3,8	11,1	3,6	18,5									
			4,2	10,8	3,7	18,7									
	16	4	3,9	10,8	3,3	18	18,43			3,78			3,55		
			3,7	10,7	3,5	17,9									
			3,7	11,3	3,4	18,4									
			3,8	11,6	4	19,4									

Table 25 - Data collection of the experiment regards the contextual factor 3: "Easiness of grasping". In this table the "Average time" and the "Standard deviation" regard the Picking, Travelling and Placing task are shown respectively.

Exp	Kit "number"	Number of parts per kit	Time to pick	Time to travel	Time to place	Time to kit	Average time to KIT a single component	AV	S.D.	Average time to PICK a single component	AV	S.D.	Average time to PLACE a single component	AV	S.D.
High Difficult Grasping	21	4	3,6	10,2	3,4	17,2	18,53	19,12	0,37	4,45	4,55	0,18	3,68	3,77	0,22
			5,5	10	3,5	19									
			4	10,7	3,3	18									
			4,7	10,7	4,5	19,9									
	22	4	4	11	3,6	18,6	19,63			4,35			3,75		
			5	13,2	2,4	20,6									
			4,5	11,1	4,2	19,8									
			3,9	10,8	4,8	19,5									
	23	4	3,7	12,5	3,2	19,4	18,98			4,78			3,50		
			5,9	10,2	3,3	19,4									
			3,9	9,7	3,6	17,2									
			5,6	10,4	3,9	19,9									
	24	4	5,2	10,3	4	19,5	19,38			4,78			4,15		
			4,3	10,1	4,2	18,6									
			5,7	10,5	3,9	20,1									
			3,9	10,9	4,5	19,3									
	25	4	5	11,5	3,6	20,1	19,18			4,48			3,88		
			5,2	10,4	3,4	19									
			3,8	10,2	4,1	18,1									
			3,9	11,2	4,4	19,5									
	26	4	3,9	11,3	3,7	18,9	19,05			4,48			3,68		
			4,3	11	4	19,3									
			4,5	10	3,2	17,7									
			5,2	11,3	3,8	20,3									

Table 26 - Data collection of the experiment regards the Comparation between the Vacuum grip and the Fingers grip. In this table the "Average time" and the "Standard deviation" regard the Picking, Travelling and Placing task are shown respectively.

Exp	Kit "number"	Number of parts per kit	Time to pick	Time to travel	Time to place	Time to kit	Average time to KIT a single component	AV	S.D.	Average time to PICK a single component	AV	S.D.	Average time to PLACE a single component	AV	S.D.
Fingers Grip	1	4	2,9	10,5	3,2	16,6	17,20	**18,40**	**0,65**	3,18	**3,40**	**0,25**	3,35	**3,48**	**0,28**
			2,9	11,1	3,5	17,5									
			2,9	10,8	3,6	17,3									
			4	10,3	3,1	17,4									
	2	4	3,2	11,8	3,8	18,8	18,35			3,28			3,18		
			3,3	11,7	3	18									
			3,5	11,8	3,1	18,4									
			3,1	12,3	2,8	18,2									
	3	4	3,5	11,2	3,2	17,9	18,38			3,13			3,63		
			2,9	11,5	3,1	17,5									
			3	11,8	4	18,8									
			3,1	12	4,2	19,3									
	4	4	4	13	4,5	21,5	19,03			3,30			3,90		
			3,3	11	3,9	18,2									
			2,9	11,8	3,4	18,1									
			3	11,5	3,8	18,3									
	5	4	3,6	10,9	4,3	18,8	19,30			3,78			3,85		
			3,8	11,1	3,9	18,8									
			3,8	12,2	4,2	20,2									
			3,9	12,5	3	19,4									
	6	4	3,7	12,1	3,7	19,5	18,50			3,48			3,50		
			3,3	12,3	3	18,6									
			3,5	10,7	3,9	18,1									
			3,4	11	3,4	17,8									
	7	4	4	11,1	3,4	18,5	18,05			3,58			3,08		
			3,5	11,3	3	17,8									
			4,2	11,1	2,8	18,1									
			2,6	12,1	3,1	17,8									
	8	4	3,9	10,8	3,8	18,5	18,98			3,73			3,50		
			3,7	12,3	3,4	19,4									
			3,5	11,9	3,4	18,8									
			3,8	12	3,4	19,2									
	9	4	3	12,1	3,2	18,3	17,85			3,18			3,33		
			3,1	10,6	3,3	17									
			2,8	11	3,6	17,4									
			3,8	11,7	3,2	18,7									

Table 27 - Data collection of the experiment regards the Comparation between the Vacuum grip and the Fingers grip. In this table the "Average time" and the "Standard deviation" regard the Picking, Travelling and Placing task are shown respectively.

Exp	Kit "number"	Number of parts per kit	Time to pick	Time to travel	Time to place	Time to kit	Average time to KIT a single component	AV	S.D.	Average time to PICK a single component	AV	S.D.	Average time to PLACE a single component	AV	S.D.
Vacuum Grip	1	4	1,6	10	2,5	14,1	14,40	**14,20**	**0,27**	1,83	**1,93**	**0,10**	2,48	**2,37**	**0,20**
			1,6	9,9	2,3	13,8									
			2	10,2	2,5	14,7									
			2,1	10,3	2,6	15									
	2	4	2,5	9,8	2,6	14,9	13,98			2,05			2,40		
			2,2	9,5	2,4	14,1									
			1,7	9,5	2,4	13,6									
			1,8	9,3	2,2	13,3									
	3	4	1,7	9,6	2,3	13,6	13,78			1,78			2,03		
			2	10,2	1,8	14									
			1,6	9,8	1,9	13,3									
			1,8	10,3	2,1	14,2									
	4	4	2,4	10,4	2,7	15,5	14,58			1,93			2,48		
			1,7	10,3	2,4	14,4									
			1,5	10,4	2,4	14,3									
			2,1	9,6	2,4	14,1									
	5	4	1,7	9,6	2,8	14,1	14,03			2,00			2,38		
			2,1	10	2,5	14,6									
			2,5	9,9	2,2	14,6									
			1,7	9,1	2	12,8									
	6	4	2	9,9	1,9	13,8	14,08			1,85			2,08		
			1,9	9,9	2,1	13,9									
			1,9	10,5	2	14,4									
			1,6	10,3	2,3	14,2									
	7	4	2,5	9,9	2,2	14,6	14,15			2,05			2,38		
			2,2	9,7	2,8	14,7									
			1,7	9,6	2,4	13,7									
			1,8	9,7	2,1	13,6									
	8	4	2	10,4	2,6	15	14,50			1,93			2,68		
			1,5	9,8	2,5	13,8									
			1,6	9,8	2,8	14,2									
			2,6	9,6	2,8	15									
	9	4	2	9,4	2,2	13,6	14,35			1,95			2,48		
			2,1	9,5	2,3	13,9									
			2,1	10,2	2,8	15,1									
			1,6	10,6	2,6	14,8									