POLITECNICO DI MILANO
Facoltà di Ingegneria dei Sistemi

POLO REGIONALE DI COMO

Master of Science in
Management, Economics and Industrial Engineering

Testing process in manufacturing: a model for optimization and an application to a real case study.

Supervisor: Prof. Alberto Portioli Staudacher

Assistant Supervisor: Prof. Donatella Corti

Master Graduation Thesis by: Luca Bennici
Elena Brenna
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732340

Academic Year: 2009/2010

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A note for the Reader

For the sake of an enhanced readability of this Thesis Work, a summary panel as the one depicted below has been inserted in some specific points within each section.
The panels are intended to provide a short summary of the concepts exposed in the sections immediately precedent, and anticipate the content of the ones immediately following.

Example

Abstract

This research aims at addressing the opportunities for performance improvement of a testing process in manufacturing.

Current trends show a general endeavor in ensuring the quality of the final product with control measures aimed at embedding quality in the process rather than controlling its output. Nonetheless, quality assurance approaches based on testing and inspection are still widely used methods in a variety of manufacturing industries in order to guarantee the final conformance to the expected quality standards.

Particularly, in a manufacturing scenario where production outsourcing is becoming a more and more common factor, testing possibly represents one of the core activities for a company whose production is completely or mostly delegated to third parts. In these cases indeed, the company becomes the final hub where the components or modules collected from a network of suppliers undergo final assembly and a quality assurance control aimed at assessing that the final product performs as expected.

It is firstly to these manufacturing realities that this work addresses to.

Three case studies of manufacturing companies where testing represents one of the core activities are going to be analyzed from the testing process standpoint.

A comparative analysis of the three case studies along with available literature on testing policies will be performed with the aim of identifying a set of significant variables for the description of a testing process.

A set of Key Performance Indicators deemed of significance for a testing process is then going to be defined, and a set of configuration guidelines aimed at improving the process performances is going to be proposed.

The output of this work will be a framework whose purpose is to represent a handy tool for a manufacturing company which is considering the opportunity of improving the performances of its testing process.

An application of the framework will be proposed on a real case with explanatory purpose. The proposed case is the result of the participation of the Authors in a company project aimed at optimizing the internal testing process.

The framework is going to be validated with another set of companies in order to appraise its strengths and limitations, and derive more tailored guidelines depending on specific business characteristics.

The conclusions of this Thesis Work with reference to the initial Reasearch Questions is finally going to be proposed, along with some areas identified as of interest for the development of future research.

Section 1: Thesis Project

Abstract

This chapter is entirely dedicated to the presentation of the Thesis Work and its related objectives, research method and main sections.

First, the method followed to address the research is presented. This part would also provide the reader with a clear explanation of the structure followed by the Thesis Work.

The prime object of this Thesis Work is then introduced. A definition of Testing Process is provided, along with a brief literature overview that proves the validity and interest of the object for the enrichment of the Scientific Community.

The research questions that are going to be addresses throughout the whole Thesis work are then introduced.

1.1 Method: literature and case studies

The research conducted for this Thesis Work presents a *Positivist* philosophical underpinning. The primary goal of research is indeed not only description, but prediction and generalization; also, the classification of substances provides the basis for descriptive laws based on consistencies in patterns and properties (Istance, 2001).

The scope of research has been defined as a manufacturing testing process presenting some peculiar characteristics.

A first brief literature overview has been carried out with the aim of assessing the academic interest of the object of research. The scope of this Thesis Work appears to fit indeed into trends identified as of interest from the available literature.

The Research Questions have been then punctually defined.

A second detailed analysis of what available in scientific literature with regards to the topic of interest has then been carried out in order to have an overview of the major findings of the scientific community on the topics of interest for this Thesis Work. Most of the readings have been done on scientific reviews, scientific journals, managerial textbooks, conference reports and companies' internal material, as it can be pointed out both in the literature analysis section and in the bibliography at the end of this volume.

The work then proceeded through a case study analysis. Case studies in the context of this Thesis Work have a *descriptive* purpose, according to the definition by Yin (1994). The aim is therefore providing a detailed picture of the issue under analysis with the purpose of creating a set of categories. A *multiple cases approach* has also been adopted in order for the “replication logic” to reveal support for either similar results or contrasting results for predictable reasons (Yin, 1994).

Three testing process case studies of significance for the analysis were therefore considered. These case studies are of quite substantial different nature. The main case study is the result of a six-month working period during which the Authors participated on a specific project within the company. The other two case studies represent the result of interviews and company visits focused on the assessment of those operational aspects of interest.

The three testing process scenarios depicted in the case studies provided the base for the definition of significant variables for the description of a generic testing process.

Furthermore, the three case studies have been benchmarked in order to define a set of best practices according to the descriptive variables that have been defined.

The following step consisted in a generalization of the findings emerged from the comparative analysis of the three case studies. This has been achieved by combining the best practices identified across the case studies with the major findings available in literature, when available. This has to be considered as an empirical approach with theoretical guidance.

The outcome of this last step is a framework of general validity which aims at proposing optimizing guidelines for a testing process on the base of a set of relevant descriptive variables for the process. As theory acknowledges indeed, in the context of a case study research the theoretical framework represents “the vehicle for generalizing to new cases” (Yin, 1994).

An example of framework application is then provided on the process presented in the main case study and the evaluation of results deriving from the implementation of the guidelines is reported.

The last phase of this Thesis Work consisted in a validation of the proposed framework. A set of validations has been carried out through interviews with Head of Operations within companies performing a testing process, and Industries Experts.

The results of the validations campaigns are proposed, along with research conclusions and proposals for future research.

Figure 1 represents the logical flow of the steps above described.

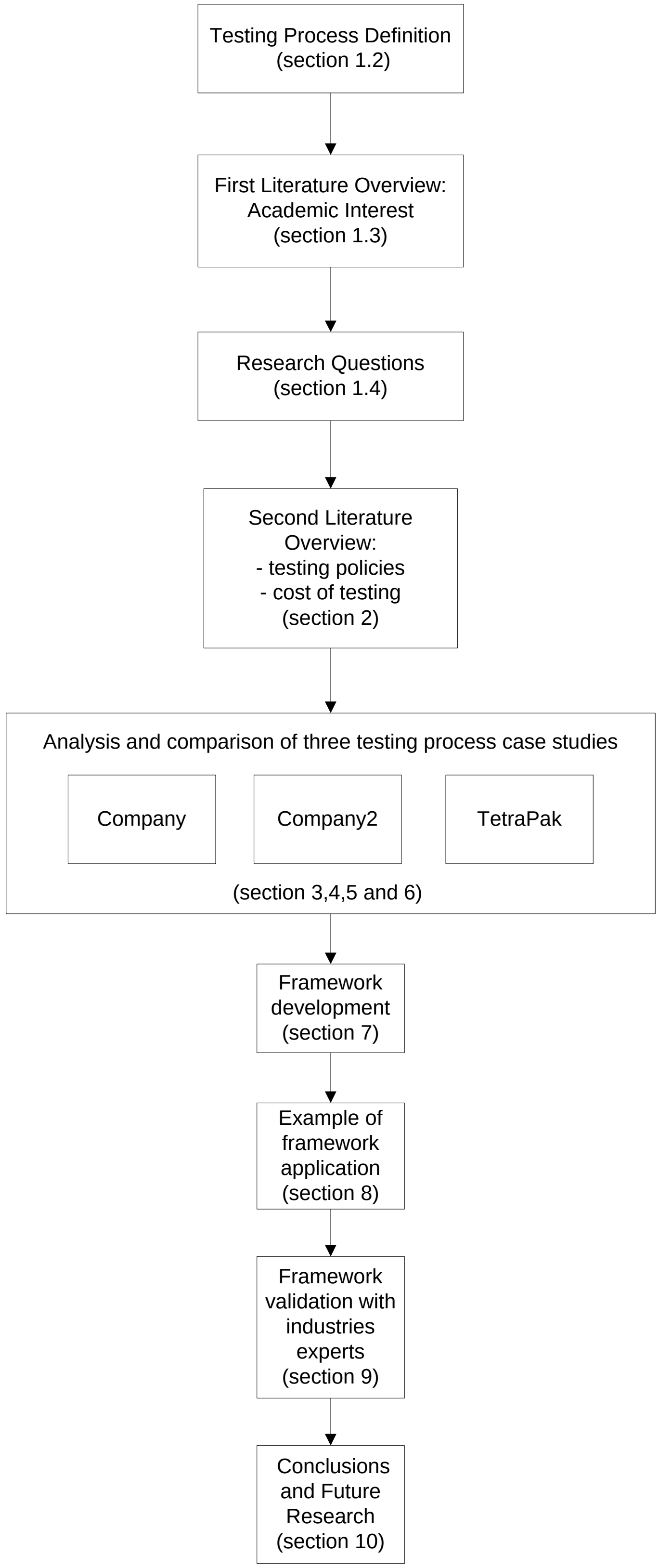

Figure 1 - Thesis Structure

1.2 Testing process definition

With reference to a manufacturing company that has totally or in a significant proportion externalized its manufacturing activities, we define as **testing process** the ensemble of testing activities on the product/system, plus a variable number of other internal activities acknowledged as tightly connected with testing, as for instance a final assembly operation on parts or modules.

1.3 Academic interest

The academic interest of analyzing a testing process as defined above is going to be assessed in the existing scientific literature. The relevance of outsourcing as a significant recent trend in manufacturing is going to be appraised, along with its impacts on quality. Product modularization and its impact on outsourcing and quality is then going to be explored; this represents one of the points which is going to be leveraged further during the development of this Thesis Work.

Outsourcing and quality-related issues

Great attention has been posed in literature on outsourcing trends in a manufacturing environment and on the identification of drivers that push a company towards the choice of externalizing partially or totally its manufacturing activities. There is wide acknowledgment in identifying outsourcing as a massive latest trend in manufacturing (Hicks, McGovern, & Earl, 2000), declined in a continuum of configurations, from local outsourcing to joint ventures and partnerships to the total outsource to service providers (Aron & Singh, 2005).

The drivers that lead a company to undertake outsourcing decisions can be of various natures. Bryce and Useem (1998) identify both cost structure and business performance as main drivers. According to Bryce and Useem (1998), cost savings explain much of the outsourcing decisions for firms with “sub-par performance records”, while an endeavor towards improved capabilities is the main driver in case of “high-cost producers”.

Hicks, McGovern and Earl (2000) identify how the trend of increasing outsourcing also interests Engineer To Order (ETO) productions, which is going to be the central focus for the main case study of this Thesis Work. Despite a lack of previous research on the topic of supply chain management applied to this kind of production, the authors identify a “trend towards vertical disintegration” for this kind of companies, mostly due to financial pressures and the need for cost reduction.

The benefits acknowledged to a properly managed outsourcing are various. Bryce and Useem (1998) identify advantages in terms of "Value Creation". Benefits are attributed to outsourcing both in terms of immediate payoffs (mostly due to less capital immobilization) and longer-term gains (due to creation of wealth for investors through investments in value-creating areas). Outsourcing can also bring along a strategic gain due to obtained synergies between user and provider.

Outsourcing decisions have been attributed pitfalls as well, along with benefits. Bryce and Useem (1998) identify how outsourcing can reduce the company value. Outsourcing can lead companies to lose "cutting-edge means to create innovative products", when cost savings deriving from an outsourcing choice become a sacrifice of future evolutionary potentials of core areas. Even when outsourced activities are not considered as core for the company's strategic advantage, they can carry interdependencies with activities that are. Outsourcing can therefore come along with the risk of jeopardizing core activities, too. Berggren and Bengtsson (2004) also note how the distinction of core-non core activities can lose any significance when considered in the context of turbulence where many businesses currently operate. Last, outsourcing exposes companies to the risk of opportunistic behavior from a business partner whose interests and objectives might be misaligned with the company's ones. According to Aron and Singh (2005), outsourcing fails to bring any benefit when companies embark on this kind of initiative just focusing on the choice of vendors, cities and countries for outsourcing without a previous focus on identifying core (those they must control), critical (those they must acquire from the best-in-class) vendor and commodity (those that can be outsourced) processes. Also, outsourcing initiatives are most likely to fail when the decision is based on a pure cost/benefit analysis without a significant evaluation of risks (Aron & Singh, 2005). Hicks, McGovern and Earl (2000) also highlight the risk of how the company can incur in a loss of "architectural knowledge" of the product if the technology critical to competitive success is outsourced.

Above all others, the quality risk in outsourcing represents the most critical issue for the kind of analysis we are addressing with this Thesis Work, due to the central focus on testing intended as a final quality control on the end product/system. Kaya and Ozalp (2004) identify an increasing importance of quality issue in outsourcing due to increased responsibilities delegated to the supplier and asymmetry of information regarding the cost of quality for the supplier itself.

It is interesting to assess the impact of outsourcing on quality dimensions. Traditional quality management systems divide quality-related costs into four categories (Kaplan & Atkinson, 1998):

- Prevention costs, such as equipment maintenance and engineering oriented towards the prevention of defective products.
- Appraisal costs, related to quality level controls by the means of inspections and testing.
- Internal failure costs, due to scraps and reworks caused by internal identification of quality problems.
- External failure costs, due to quality problems identified by the customer.

There is wide agreement in identifying outsourcing as a significant recent trend in manufacturing. A relevant degree of correlation is identified between outsourcing and the existence of quality-related issues due to the externalization of production, especially in those cases where quality control is delegated to the supplier.
We are now going to consider the correlation between outsourcing and product modularization. Modularization is going to be one of the points of major interest during our analysis, particularly for those aspects related to the isolation of test procedures that can be performed on individual product modules and delegated to the module manufacturer, if any.

Modularization

From the standpoint of a testing process as we defined it, it is interesting to introduce the concept of product modularization in relation to outsourcing and to quality issues related to outsourcing.

Module has been defined as "a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units" (Baldwin & Clark, 2000). Arnheiter and Harren (2006) also add that a module can be thought of as a "self-contained sub assembly that connects to other modules using common interfaces", and modularity as "the use of modules to facilitate assembly and customized configurations of finished products".

Ulrich (1995, p. 419) proposes a definition of modularity in relation to product architecture. Product architecture encompasses

- "The arrangement of functional elements, which is how the different functional requirements are structured in order to contribute to the total product performance".
- "The mapping from functional elements to physical components, that means which component implements which function".
- "The specification of the physical components' interfaces".

According to Ulrich (1995, p.419), in a modular product architecture there is "one-to-one mapping between physical components and functional elements, and the interfaces between components are decoupled". On the opposite, an integral architecture presents a "complex mapping between physical components and functional elements, and coupled interfaces between components". The author also suggests how, according to these different characteristics, integral architectures emphasize product performance, while modular architectures emphasize product change, variety, flexibility and upgradeability.

The definition of modularity can nonetheless vary significantly across industries. With regards to this aspect, it is of particular interest a study performed by Ishii and Yang (2003) to benchmark modularity practices across industries. As Ishii and Yang (2003) underline in their project approach statement, modularity is a very broad concept that applies differently to different products, and depending how modularity is applied "its value can be measured in different forms". In general, the authors identify that:

- Complexity is the main driver for modularity.
- Value and form of modularity depend on specific drivers related to the industry.
- Modularity is scalable from a business to a product development strategy.
- Modularity at a business level must consider the availability of resources including supply chain.
- Modularity at product development level is a "set of design rules derived from industry specific drivers".

As for the drivers that characterize modularity depending on the industry, the authors propose the result of a cross-industry survey. The responses on the definition of modularity tend to be of two kinds: "Product oriented" and "Non-product oriented". Non-product oriented definitions, just take into account "producibility" and "supply chain" factors. Product-oriented definitions take into account the "whats" (the object of modularity), the "hows" (the activities to achieve modularity), the "intos"(the outcome of activities), the "withs" (the rules to be considered in the overall process) and the "fors" (the goals of modularity in terms of product development). The two definition schemes are represented in Figure 2.

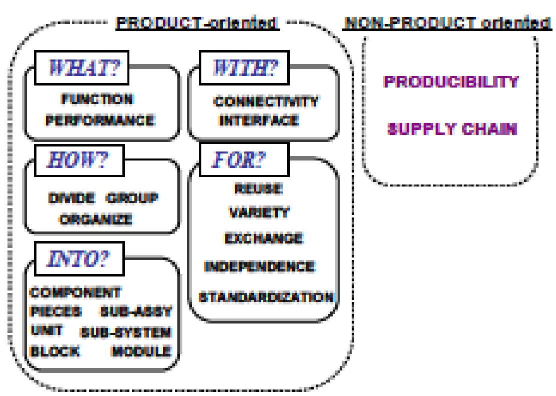

Figure 2 - Results of a cross-industry survey on the drivers characterizing the modularity

Impact of product modularization on supply chain design

It is of interest for our analysis to consider the impacts of product modularization on supply chain design. There is generally wide agreement within the scientific community on the fact that there is a critical influence of product modularity on supply chain configuration.

Ernst (2005) identifies how technical modularity "has created opportunities for vertical specialization in project execution, enabling firms to disintegrate the value chain as well as disperse it geographically".

Howard and Squire (2007) state that decisions related to modularization apply not only to the products themselves, but also to the organizational design in its broad sense, where tasks related to the product are performed "concurrently and autonomously by a loosely coupled structure of organizations". In their analysis of the impacts of modularization on supply chain, the authors identify how two aspects impact on the creation of a collaborative relationship along the supply chain given product modularization. These are:

- Presence of relationship specific assets. This is particularly true when modularization involves the supply chain since the product design phase that requires capital intensive equipment.
- Information sharing. Since modularization increases information sharing, the need would be addressed for information sharing on production alerts, production scheduling, etc.

Lau and Yam (2005) suggest that modular design has a plurality of effects on supply chain design and performances. Particularly:

- Supply chain for modular product design has one more level than multi-tier supply chain for integrated product design. This is due to the presence of a layer of components suppliers, a layer of modules manufacturers and the layer of the final assembler or "system integrator". This condition raises the need of enhanced communication when manufacturers decide to outsource modules production.
- Properly combined decisions on modular product design and supply chain design lead to both reductions of overall production costs and improvements in supply chain performance. Since the standardized modules are widely separated and their interfaces are well defined, they can be outsourced to module suppliers in a very loosely integrated manner. Also, as each product module is independent from the others, each supplier is just required to stick to the module specifications without considering any other module modification.

With regards to the "system integrator", or extra tier, Brusoni and Prencipe (2001) acknowledge it a crucial coordination role. According to the authors indeed, the system integrator has to keep capabilities that span over a wide range of technological fields, actually wider than the range of activities which are performed in-house; as to say, they should "know more than they do" (Brusoni & Prencipe, 2001). The authors analyze this aspect in the aircraft engine industry. It emerges from their analysis that companies operating in this sector are not mere assemblers of components, but they indeed play a key role in design, development and integration, keeping a fundamental understanding of what they outsource. On the base of this analysis, system integrators are identified as maintaining focus on their "softer capabilities" while outsourcing the "hard ones".

Salerno and Dias (1999) also stress the importance of supplier proximity in order for the modular system to perform at its best. According to Salerno and Dias, proximity plays the following role:

- Reduction of logistical costs of modules/subassemblies.
- Reduction of inventories at the final assembler's site.
- Creation of a better service relation. This implies the creation of a hands-on-quality situation for the final assembler, especially in those cases when the modules represent a "black box" for the final assembler due to internal complexity.

By analyzing the concept of product modularity and its interaction with the design of a supply chain, it emerges that modularity has a positive impact in the creation of opportunities for vertical disintegration.
We are now going to consider the possible impacts of modularity on quality. This is of fundamental importance due to the focus of our analysis on test as a quality assurance method.

Modularization from a quality standpoint

From a quality standpoint, subassembly or module supply means that the final assembler "receives less but much more important parts, with a greater value added" (Salerno & Dias, 1999). The supplier is therefore attributed the greater responsibility of ensuring delivery and quality conformity to the whole module or subassembly. As Salerno and Dias highlight, this is a significantly different perspective from the one that attributes to the supplier the sole responsibility of a single part that would be further manufactured downstream its process. From a quality assurance standpoint, a modular approach to supplies means that if the quality of modules is ensured upstream at the supplier's stage, the identification of quality issues is much easier downstream in the process, since errors can just occur in the final assembly phase (Ntafos, 1998). In this sense the "modular system" (Salerno & Dias, 1999) allows easier setting of responsibilities concerning quality issues compared to the traditional system. For what it concerns highly integrated products based on complex technological platforms, Ciarli, Leoncini, Montresor and Valente (2007) suggest that a determinant factor for the possibility of these products to be explored with a modular strategy is given by the presence of "fully informed" suppliers specialized per modules that can guarantee the follow-up of the product technology and architecture, operating as if they were part of the customer. When a long-term advantage is identified in the opportunity of outsourcing modules manufacturing, and the prior condition is guaranteed, the firm would undertake an outsourcing initiative. Whenever the supplier does not meet any longer the technological requirements or does no longer suit the product architecture, the firm would start considering either the change of supplier or the reintegration of module/s production.

Arnheiter and Harren (2006) analyze the impact of modularity on quality, being quality declined in a set of interrelated dimensions. The authors identify "eight key attributes" of quality, namely:

- Aesthetics, defined as the product appearance, feel, taste, etc.
- Perceived quality, as the subjective reputation the product accrued over time concerning quality-related aspects.
- Performance, defined as the main operating characteristics of the product.
- Conformance, defined as the "extent to which product characteristics fall within design specifications".
- Features, as additional characteristics on top of basic functioning for the product.
- Serviceability, as the ease of access and user-friendliness of services related to the product, as for instance repairing.
- Reliability, as the probability for the product to incur in a failure over a certain period.
- Durability, as a measure of the useful life for the product.

The impact of modularity over these quality dimensions has been appraised as being two-folded. Concerning the effects over each and single dimension, modularity impacts as follows (Arnheiter & Harren, 2006):

- **Aesthetics.** Modularity can imply a multitude of small parts combined into a few modules; this can have a positive impact on the product's aesthetics, especially when modules are visible to the end user. On the other side, modularity can have a negative impact when the need for well defined interfaces constrains the possibilities of product design.
- **Perceived Quality.** No obvious positive impacts of modularity have been identified over this variable. On the other side, the reuse of same modules across different product line can negatively impact this dimension.
- **Performance.** No obvious positive impacts of modularity have been identified over this variable. As opposite, the use of generic modules or modules with levels of performance

different from the ones required by the customer can have a negative impact on this dimension.

- **Conformance.** If the modules suppliers have a production and quality systems equivalent to that of the final assembler, then a positive impact of modularity on this dimension is achieved. In more traditional systems the quality inspection is typically a prerogative of the final "system integrator"; in a modular supply chain, due to the higher level of cooperation required by modules manufacturers and final assemblers, most of the quality inspection is delegated to modules manufacturer, while the final assembler keeps the prerogative of final control over the modules interfaces. The negative impact of modularity on conformance is mostly related to the issue of outsourcing rather than modularity itself. If the supplier indeed does not provide adequate levels of quality conformance, modularity will have a negative impact on this dimension.
- **Features.** No evident benefit appears in relation to the quality of product features due to modularity; on the opposite, a clear positive impact on the ease of product customization is acknowledged to modularity. Due to the usage of common interfaces, modularity allows indeed the mass-customization of a product in terms of different features without affecting the product's performances. No obvious negative effects of modularity on this dimension are identified.
- **Serviceability.** An increase in service speed is acknowledged to modularity; the standardization of interfaces among modules allows indeed an easy replacement of individual modules when needed. As opposite, modularity will have a negative impact on this dimension when the failure of a single component implies the replacing of the whole module, being the module the highest level of granularity in the product architecture.
- **Reliability.** Modularity can have a positive impact on reliability in a few ways. For the scope of our analysis, it is interesting to highlight the positive impact identified on enabling independent module development and testing. This allows subassemblies to be tested before they enter the final assembly by defining special "test routines" for each individual module or subassembly. This implies that if modules are of proven quality when entering the final assembly test, the final quality check can be performed only on the few steps of the final assembly. No obvious negative effects of modularity on this dimension are identified.
- **Durability.** Modularity is acknowledged having a positive impact on this dimension since it allows eased product upgrading. No obvious negative effects of modularity on this dimension are identified.

Ishii and Yang (2003) identify a set of anticipated benefits that can arise from modularity. This set includes "better quality" as one of the benefits. The authors identify two major sources of positive effects due to modularity:

- **Per-module testing.** Modules can be tested separately and individually before they reach the assembly line. This implies that the module "carries validated quality", independent of the assembly related errors. At that point only the errors related to system integration would affect the final quality.
- **Decreased complexity in assembly.** The complexity of assembly drastically decreases if the assembly activity has to operate with modules instead of numerous parts. Since an inverse relationship has been identified between assembly complexity and product quality, it is possible to highlight the positive effect of modularity on quality through the simplification of assembly operations.

On the opposite, Ishii and Yang (2003) also identify a possible pitfall from modularity impacting on the quality of the final product. From a holistic perspective, a doubt arises whether "good + good + good = good?" (Ishii & Yang, 2003); due to the presence of interfaces between modules that compose the end product, the overall product quality may not be ensured until the last integration step takes place, independently from the quality level of each module.

> The impact of product modularization on quality has then been analyzed.
> Modularity appears to have both positive and negative impacts on quality, according to some defined quality measures.
> With regards to those quality aspects that are mostly related to supply chain, it emerges a positive impact of modularity on quality when the suppliers present the same level of quality conformance as the final assembler, so to allow the system integrator to perform only the final integration tests

Conclusions

The interest and academic validity of our study appears to be supported by the analyzed literature.

There is wide agreement in identifying outsourcing as a significant recent trend in manufacturing (Hicks, McGovern, & Earl, 2000) (Aron & Singh, 2005) (Bryce & Useem, 1998), and a relevant degree of correlation is identified between outsourcing and the existence of quality-related issues due to the externalization of production (Kaya & Ozalp, 2004) (Kaplan & Atkinson, 1998), especially in those cases where quality control is delegated to the supplier (Kaya & Ozalp, 2004).

By analyzing the concept of product modularity and its interaction with the design of a supply chain, it emerges that modularity has a positive impact in the creation of opportunities for vertical disintegration. The role of the final system integrator also appears as crucial within the supply chain (Brusoni & Prencipe, 2001).

The impact of product modularization on quality has then been analyzed. Modularity appears to have both positive and negative impacts on quality, according to some defined quality measures (Arnheiter & Harren, 2006). With regards to those quality aspects that are mostly related to supply chain, it emerges a positive impact of modularity on quality when the suppliers present the same level of quality conformance as the final assembler, so to allow the system integrator to perform only the final integration tests (Ciarli, Leoncini, Montresor, & Valente, 2007) (Salerno & Dias, 1999) (Ishii & Yang, 2003) (Ntafos, 1998).

We can conclude that:

- Outsourcing in manufacturing is a significant actual trend. It is therefore of interest to analyze improvement opportunities within a testing process based on the premises of outsourced production.
- Outsourcing brings along quality issues due to the loss of direct control on some manufacturing activities. It is therefore of interest to analyze improvement opportunities within a testing process while considering the consequences of a possible trade-off emerging from outsourcing (as a premise of the process) and quality control (as the central aim of a testing activity).

and

- Product modularity positively influences the possibilities of outsourcing. It is therefore of interest to analyze improvement opportunities within a testing process while considering the opportunities for modularization; modularization indeed possibly increases the outsourcing premises of the testing process, considering them as a desirable condition for the reasons mentioned above.
- Product modularity impacts both positively and negatively on product quality, according to different quality measures. It is therefore of interest to analyze improvement opportunities within a testing process while considering the possible chain-effects that can originate from the interaction of the three aspects of modularity, quality and outsourcing.

1.4 Relevance and criticalities of testing

Concerning quality, there is wide acknowledgement of the fact that preventive measures outperform appraisal ones (Singer & Donoso, 2009); nonetheless, the presence of testing activities is still relevant in various industries, as the number and variety of companies consulted for the development of this Thesis Work also demonstrates.

Product inspection and testing continue indeed to be "an important means to ensure outgoing product quality, as most of the production processes are stochastic and dynamic in nature" (Shaoxiang & Lambrecht, 1997). On the other hand, the benefit in terms of quality assurance is counterbalanced by the cost and time consumption of the test activity itself (Mital, Govindaraju, & Subramani, 1998). As product margins shrink, indeed, "the cost of testing during the manufacturing process becomes a significant part of total manufacturing cost" (Johnson, 2005), in some cases approaching percentages as significant as 50% of the manufacturing costs (Grochowski, Bhattachrrya, Viswanathan, & Laker, 1997).

Given this evidence of impact, it is of interest to assess which can be identified as the general criticalities of a test activity; these could provide hints on which areas to tackle in order to generate a situation where the benefits of testing outweigh the costs.

The criticalities of a generic testing process have been defined by the means of assessments with Chiefs Operation Officers within companies that internally perform a testing process analogous to the one defined.

A set of seven companies has been considered for this assessment, including two companies operating in the filling machines industry, three companies operating in the packaging machines industry, one company operating in the gearmotors industry, and one company operating in the production of complex electronic systems whose application cannot be disclosed.

Some of the aspects characterizing a testing process that have generally emerged as critical factors are:

- **Stochastic nature of testing process determines Lead Time and Cost variability.** The combined probabilities of detecting errors at different stages of the testing process determines a variability in the process itself; the detection of an error triggers indeed the error-solving phase, which might be requiring complex interfaces among different types of professional figures within the company. This characteristic of the testing process determines variability in the Lead Time, which is in turn acknowledged as a source of loss of system performances (also according to traditional Lean thinking, as for (Standard & Davis, 2000)). As a consequence, the cost accrued by testing can vary according to the number and type of errors detected, and the time and resources needed for their resolution.

- **Activity execution highly dependent on the output of the previous activity.** Unlike a production process, where the linkages between consequent phases are defined, testing process presents a complex branching of activities depending on the positive or negative outcome of the previous stage. Whereas a positive outcome allows a direct linkage to the following test step, a negative outcome triggers a series of actions targeting the error cause resolution. This brings along organizational complexity and potentially unleveled workload for those professional figures that intervene in the process whenever a certain type of error is detected.
- **Complexity in defining exhaustive tests that minimize the probabilities of both type I and type II errors.** In some cases, the definition of a set of tests which is able to guarantee the coverage of all the functional requirements expressed for the product represents a critical element of a testing process, with possible repercussions on the final quality of the outbound product (type II errors), or on the cost of production (type I errors) (Shaoxiang & Lambrecht, 1997).
- **Error propagation phenomenon.** The failure in identifying an error arising during a test procedure can generate a propagation of the error itself, so that the identification at a later stage might require the product to undergo test procedures that have already been performed. This phenomenon can be compared to a situation where the defective output of a productive stage is not detected and undergoes a series of subsequent phases until the defect is detected n stages downstream, giving rise to a need for rework. This generates losses in efficiency within the system, and duplication of activities (Ntafos, 1998)

1.5 Research Question

The chosen Research Questions to be addressed with this Master Thesis work are the following:

1. "What descriptive variables can be identified in order to characterize a specific testing process[1]?"

2. "What configurations can be proposed for the improvement of a specific testing process[1] depending on different business characteristics?"

[1] With reference to the definition provided in section 1.2

Section 2: Literature Analysis.

Abstract

The literature overview has been analyzed according to two main streams deriving from the choice of focusing the Thesis Work on a testing process whose specific characteristics have been defined in section 1.2.

A first literature analysis is going to be carried out with regards to the main components impacting on the cost of testing. Cost of testing has indeed been identified as an increasingly important factor generating trade offs with the desired confidence level over quality outputs.

A second literature analysis is going to be carried out with regards to the testing activity itself and the main policies governing it, on the base of the analysis of testing in two industries of interest. This will provide an overview on the main drivers guiding the choice of a specific test approach in relation with objectives and contextual constraints.

Figure 3 represents the structure of this section.

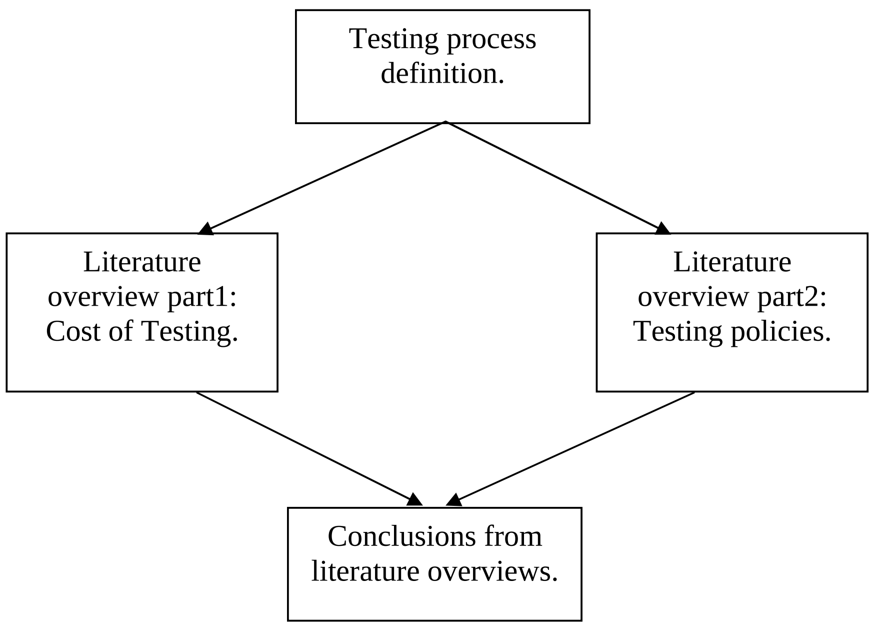

Figure 3 - Literature structure

2.1 Literature overview 1: cost of testing

Cost of testing is identified in literature as one of the major components of Cost of Quality (i.e. the grand sum of all costs incurred by investing in the prevention of non conformance, appraising the product's conformance and failing to meet requirement (ASQ Quality Costs Committee, 1999).

Figure 4 represents the decomposition of Total Cost of Quality into its main elements (Basu, 2004).

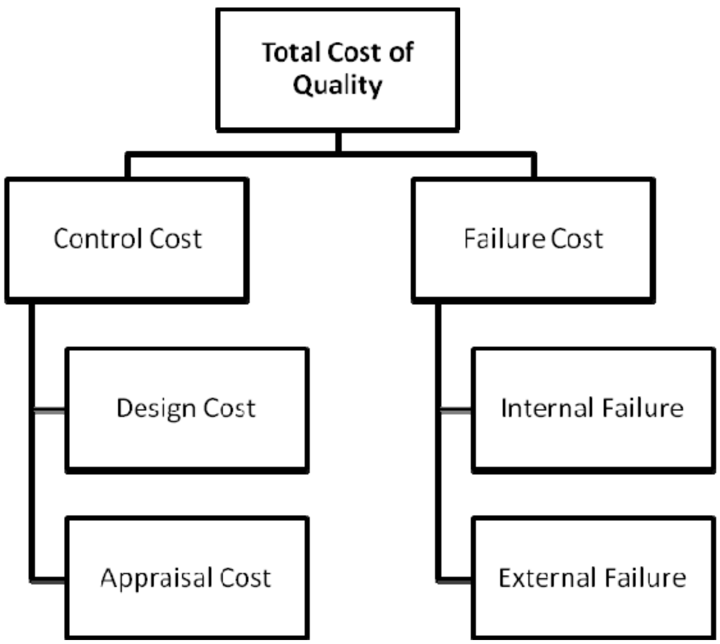

Figure 4 - Main elements of the Total Cost of Quality (Basu, 2004)

We can identify:

- Cost of Prevention (Design) and Cost of Testing (Appraisal), which generally rise with increasing quality.
- Cost of Internal Failure and cost of External Failure, which fall with increasing quality.

The emphasis is posed in Prevention, so that all the costs related with testing and inspection, external and internal failures would decrease.

It is also important to stress that, according to the law of diminishing returns, there is a point where the investments in quality improvement (Prevention and Testing) will become uneconomical compared to the marginal benefits they would bring along. Basu therefore suggests that "the ethic of continuous improvement should aim at appropriate level of quality and then sustain it" (Basu, 2004).

It is of interest for the analysis performed within this Thesis Work to analyze the main components and the factors impacting on the Cost of Testing.

Keeping laser diodes manufacturing as the reference field, Johnson (2005) defines a formulation for the cost of testing. He identifies some major components of the total cost figure, namely:

- Fixed costs. Fixed costs in testing include "the capital cost of the equipment amortized over its useful life", plus the cost of engineering required for the development in-house of specific test systems.
- Recurring costs. Variable costs incurred during testing, such as the cost of test personnel, engineering costs to maintain the cost system, facility costs, consumable items and maintenance.
- Production yield. Yield represents the number of good parts give as output of the testing process divided by the number of parts tested.
- Utilization. Utilization represents the fraction of time that the test system is in use.
- Testing throughput. Throughput indicates the number of product units tested per unit of time.

Johnson proposes the aggregation of the major components above defined as follows:

$$\text{Cost of test} = \frac{\dfrac{\dfrac{\text{fixed costs}}{\text{lifetime}}}{\text{Utilization} \cdot \text{throughput}} + \text{recurring costs}}{\text{yield}}$$

Each of the terms defined above has a direct impact on the final figure of cost of testing; therefore the cost of test can be reduced by working on each of those terms.

- Fixed costs. The impact of the initial cost of the test system should be taken into account. The minimization of the initial cost should be indeed evaluated by taking into account the alternatives in investing in equipment rather than in in-house design, debug and qualification and manufacturing of the system.
- Testing throughput. The presence of highly manual testing procedures can limit the upper bound for throughput. Improvements in this sense are given by the introduction of relatively

simple levels of automation and the reorganization of testing so to proceed in batches whenever possible.

- Recurring costs. Depending on the industry, labor can have a greater or lesser incidence in this cost figure. The introduction of batch processing and test automation can generally have an impact in reducing the incidence of labor cost. Also, the design of simple tests procedure can lower the skills requirements for testing operators, therefore having a positive impact on this cost component. The selection of equipment with a high degree of built-in analysis helps on the other side to minimize requirements in terms of test engineering, which also impact on this cost figure.
- Utilization. An increase in utilization has a positive impact on the total cost of test. Higher utilization rates can be achieved in different ways. It can for instance be achieved by extending the operative time of the test system (for instance by identifying tests that can be run unattended beyond the eight-hour day). Other solutions can be the improvement of system uptime, so to reduce the downtime needed for repair and maintenance (Deaton Engineering Helps Dell Quality Test 450 Cooling Fans Simultaneously). The impact of improving utilization is anyways higher in those cases where a significant portion of the total cost is given by capital equipment and other fixed costs rather than by cost of labor.

The issue of cost of testing can be also tackled from the perspective of test imperfection. The total cost of test as above analyzed does not take into consideration the costs arising from the need of repeating tests whenever the outcome of the test itself cannot be guaranteed. Items that are classified as nonconforming may indeed be conforming (type I errors), and on the other way around items that are accepted as conforming may be defective (type II errors). As the need of inspection should be justified in terms of the costs involved, and the inspection costs might be different depending on the product characteristics not all tests can be cost effective to be conducted, while some might be justified in being executed more than once (Shaoxiang & Lambrecht, 1997).

The choice of allocation of inspection resources, which can be either 100% or sampling-based inspection (Vaghefi & Sarhangian, 2009) (Rau & Cho, 2009) (Rau & Chu, 2005) appears to be mostly constrained to the peculiar features of the production process (Vaghefi & Sarhangian, 2009) (Rau & Cho, 2009).

From a cost-reduction perspective, it is interesting to consider whether it is better to repetitively test rejected items or accepted items. Ding, Greenberg and Matsuo (1998) analyze this problem from the perspective of semiconductor manufacturing industry. The industry is classified as extremely capital intensive, and both shipping non conforming items and rejecting conforming items imply high costs. The performed analysis lead the authors to identify as a more cost-efficient solution the practice of repetitively testing rejected items, as opposite to "repetitively test accepted items as commonly assumed in literature".

Shaoxiang and Lambrecht (1997) suggest that the sequencing of tests should be done in such a way to arrange relatively expensive tests in a second stage compared to relatively less expensive ones; if the expensive tests are arranged last, indeed, “part of the inspection cost will be saved, as some of the components will be rejected by earlier but less expensive tests” (Shaoxiang & Lambrecht, 1997).

Also, it is object of accurate analysis where in a multistage production system it is better to locate inspection stations in order to minimize the impact of a defective part moving along the production chain. Rework costs increase indeed after each successive production step (Kakade, Valenzuela, & Smith, 2004). This is acknowledged as especially significant for products with “multiple quality characteristics” (Shiau, Lin, & Chuang, 2007).

Shiau, Lin and Chuang (2007) identify as a preliminary idea the one of maintaining an outgoing inspection, which coincides with an inspection station after the last manufacturing stage. The drawback of this solution consists though in a loss of those manufacturing costs corresponded to the production of defective items. A solution proposed in order to overcome this problem consists in the placement of inspection stations after “each major manufacturing process”. In this case the defective items are prevented to continue the manufacturing process and scrapped or sent back to rework immediately after detection. Fragoso-Diaz suggests that ideally companies should inspect at every manufacturing stage in order to “respond to problems as quickly as possible”. The increase in number of inspection stations nonetheless increases the cost of resources assigned to inspection, therefore creating a trade off with the benefit of quick error identification. The author identifies therefore as cost effective to “reduce the number of inspection stations and to assign them only to some stages of a process”.

As an evidence of this we can consider a study of inspection practices within the circuit boards manufacturing industry (Chevalier & Wein, 1997), where the case of Hewlett Packard is presented. The circuit board testing process is carried out within the company concurrently to the assembly phase. The testing process is composed by different phases, where “successive tests are increasingly comprehensive … and the cost of disassembling a unit to repair a defect increases as the unit progresses along the line”. Inspections are therefore carried out at different stages; this prevents defects arising from a certain number of previous manufacturing steps to move along the manufacturing chain causing increased costs of detection and rework.

Also, Shiau, Lin and Chuang (2007) highlights the importance of manufacturing process and inspection planning being carried out concurrently, as opposite to current practices that see the two activities conducted separately. The benefits of a concurrent development would consist in a “minimization of the process costs while meeting all the specified requirements” (Shiau, Lin, & Chuang, 2007).

Cost of Testing is one of the principal components of Total Cost of Quality.
The components of Cost of Testing can be identified as fixed costs, recurring costs, production yields, utilization and test throughput. Each of them can perform as a lever in order to reduce the total cost of testing without impacting on the outcoming quality, if targeted with specific actions
The Cost of Testing is impacted by specific choices of policies for testing, which can vary depending on different primary objective, such as the reduction of errors of type I and type II.
An overview of the main testing policies within different industries is now exposed, with the aim of highlighting different testing policies depending on specific objectives and constraints.

2.2 Literature overview 2: testing policies

2.2.1 Overview on the main testing policies

An analysis of available literature on testing practices across various industries points out the existence of a series of different testing policies, as follows:

- Random testing
- Adaptive random testing
- Partitioning testing
- Divide-and-conquer testing
- Regression testing
- Module testing
- System integration testing
- Parallel testing
- Concurrent testing.

It needs to be brought to evidence that the list presented doesn't aim to be comprehensive of all the possible test methodologies used in various industries. The main focus in this section of the literature overview is indeed to provide a comparative analysis of the most significant approaches to tests in use within those manufacturing industries where the testing process represents the core activity, accordingly with our testing process definition.

Two industries are particularly considered due to the emerged relevance of testing activities within their processes: software development and semiconductor manufacturing industries.

2.2.2 Testing in a software development industry

A review of the testing process in the software development industry is carried out as follows:

- Definition, Advantages, Disadvantages
- Main software development testing methods
- Testing sequencing and Complementary aspects of the different testing methods
- Modular and parallelization software testing methodology
- Approaches to software testing.

Definition, advantages and disadvantages

Independently from the specific software testing methodology, a software testing process is composed by the following activities (Harrold, 2000):

- Test case design.
- Software execution with test cases.
- Results examination.

Testing within the software industry presents three main strong points according to Harrold (2000):

- Ease in carrying out the testing activities.
- Software execution carried out within its expected environment.
- Possibility of test cases automation.

On the opposite, the drawbacks are identified as (Harrold, 2000):

- Software test cannot prove the absence of faults.
- Testing cannot prove that the software has certain qualities.

- Lack of generality for some test execution results.

It is also of interest to highlight another aspect that has emerged from the literature review which is the common reason which drives software companies to test their products.

According to Chen, Kuo, Merkel and Ng (2004) and Harrold (2000) testing is carried out to ensure software quality. On the same line of thought is also Ntafos (1998) who identifies program testing as the main method to achieve a good confidence level on software reliability. The cost of field failures outweighs indeed the cost of testing, therefore making the cost of appraisal preferable to the cost of external failures.

In particular, in software development industry the testing process represents a high portion of the total cost accrued during the whole manufacturing process. According to Harrold (2000) "more than 50% of the cost of software development is devoted to testing".

Main testing development methods

The testing process in software development depends on the requirements that each individual company decides to embrace and the type of software it needs to develop.

In particular Weyunker and Jeng (1991) provide an overview of two types of tests: partitioning exhaustive testing and partitioning random testing. In general, partitioning testing methodologies involve the division of the program's input domains into subsets; one or more elements at a time are then chosen from each sub domain to undergo tests. Given this general definition, Weyuker and Jeng (1991) refer to exhaustive partitioning test as the testing technique implicating "every element of the input domain is to be explicitly tested". On the other hand, the random testing policy implicates the testing of just a random sample of element within the input domain.

Weyuker and Jeng (1991) also provide insight about the performance characteristics of these two types of testing methodology. Performing exhaustive partitioning tests is more expensive than performing the same number of random tests, therefore making the first method "less cost effective in terms of cost per fault found". Ntafos (1998) also agrees on that and states that "the real issue about partitioning testing is its cost effectiveness compared to random testing".

Random testing is not the only testing methodology which includes an unpredictable choice of elements to be tested, though. Ntafos (1998) has introduced an enhanced form of random testing which outperforms the previously introduced methodology. This testing policy is named adaptive random testing and is based on a more even distribution of the test cases within the input space.

The same line of thoughts is also shared by Chen, Kuo, Merkel and S.P. (2004) who do underline the general and wide spread adoption of the random testing method in the software development industry, but at the same time underlines its limitations compared with its enhanced variants. According to Chen, Kuo, Merkel and S.P. (2004) in fact "random testing is a poor method because it does not make use of any information about the program or specifications to guide the selection of test cases" while its enhanced variants do.

Another testing methodology which is analyzed in the literature is regression testing. According to Onoma, Tsai, Poonawala and Suganuma (1998) the peculiarity of this testing policy is that despite it is born within the field of software development and maintenance it can be useful for a broader set of companies which shares some common characteristics. Onoma, Tsai, Poonawala and Suganuma (1998) lists them as follow:

- "Companies developing a family of similar products by reusing products or test cases they had developed before".
- "Companies developing mission critical, safety-critical, or real-time systems because they need to test and retest their software frequently".
- Companies maintain large programs over a long period of time.
- Companies developing software in an informal way (with respect of the more formal methods used by code developers).
- "Companies that do not use software inspection as one their quality assurance techniques".

The author then continues in his article by listing all the necessary steps to carry out a regression test. These are out of the scope for the literature review of this Master Thesis, though we refer to it for further details. One aspect that we thought of interest to analyze of Onoma, Tsai, Poonawala and Suganuma's (1998) work is the dependency issue. Due to the software development modular testing it can happen that several people do not know that they are working on the same programs or on programs which depend on each other. The solution that Onoma, Tsai, Poonawala and Suganuma (1998) propose is to submit all tester's programs or modification request for evaluation. In this manner in fact if a fault has been detected in a module it's easier to manage the removal of all the modules and programs that were depending on it.

Another interesting analysis in Onoma, Tsai, Poonawala and Suganuma's (1998) work regards the approaches to the fault mitigation. According to Onoma, Tsai, Poonawala and Suganuma (1998) these are:

- Creating a new program modification card (PMC) to correct the faults detected in another PMC.
- Removing the PMC that caused the fault to happen from the software. This approach has to be weighed with the number of dependencies that PMC had. In fact all PMCs dependent on the PMC candidate for removal needs to be removed as well. As a consequence the larger the number of dependencies, the lesser the appropriateness of this approach.

Testing methods sequences and their complementary aspects

Another aspect of relevance is the situation in which the different software testing methodologies can be used together or alternatively one excluding the other one. Regarding this aspect the academic authors embrace different schools of thoughts.

Different authors have indeed different opinions about both the phase of the testing process in which a particular testing methodology is better suited to be used and about the complementary of each testing methodology with respect to the others.

In particular Ntafos (1998) does agree on the complementary issue of the random testing and argues that this testing methodology is suitable for the final testing.

On the other side the authors Loo and Tsai (1988) do agree about the possible complementary of the random testing, but it limits it with the partitioning testing only. Moreover, the authors suggest that random test should be used at early stages of the testing process followed by the partitioning testing. According to Loo and Tsai (1998) this testing sequence allows the software testing costs to be reduced.

Modular and parallelization software testing methodology

An extension of the regression testing is the multi-level regression testing (MLRT) which is used to develop large programs. These large programs have some peculiarity with respect to the other programs which derive from their bigger size. In fact due to their larger size they are developed following a waterfall approach. Therefore the large program is decomposed into components, which in turn are further decomposed.

Another peculiarity of such large programs is that they are tested at multiple stages. Furthermore the testing process itself is composed of different types of tests (Onoma, Tsai, Poonawala, & Suganuma, 1998):

- Unit testing
- Multiple levels of integration testing
- Functional testing
- Reliability testing
- Usage testing
- Stress testing
- Acceptance testing
- Field testing.

The logic according to which such programs are tested follows the divide-and –conquer strategy. This implies that if a module has been changed it must be submitted to the unit regression testing before its integration with other modules is verified.

According to Onoma, Tsai, Poonawala and Suganuma (1998) the MLRT method has several advantages over the regression testing:

- “Test suites can be attached to each software component at different level of granularity”.
- Parallelization of component’s testing.
- Delay minimization in detecting faults.

Approaches to software testing

The authors Onoma, Tsai, Poonawala and Suganuma (1998) also identify two approaches to software testing.

- Application environment simulation. This testing approach consists in creating an application environment which simulates the real conditions under which the software will be used. Users are invited to test the product for some period. These simulations are then also used for further releases and they are taken in great consideration since they represent the customer’s view of the software.
- Acceptance test or test cases supplied by users. This situation is verified when the users provide the software company with a good set of test cases based on bugs they have previously encountered. Therefore, the bugs become test cases.

Another approach to the testing process which has a general applicability is the testing postponement. This approach is investigated in the article “Mass customization at HP: the power of postponement”.

The authors Lee and Feitzinger (1997) present the case of the HP’s disk-drive division and he compares the old testing approach with the new one. Under the old testing process, it was practice for HP to insert a printed circuit board before the testing process. As a result once the board was inserted, the disk could only be bought by the specific customer who ordered it. At that time, though, the HP’s disk-drive customers often reviewed their orders, thus creating problems for the division to accommodate such changes during or after the testing were performed. The solution to such a problem was separating the test in two sub-tests: a standard one through which all the products must have passed before reaching the customer, and a second one consisting of a customized test specific to the individual end product. The concept of testing postponement comes from the fact that HP ran all the standard test process before a customer order. Afterwards when they received the order they performed the customized test according to the specific circuit board the customer required.

2.2.3 Testing in semiconductor manufacturing industry

Another industry which is characterized by an absolute importance of the testing processes is the semi-conductor one.

As for the software development testing process also the IC testing process constitutes a big portion of the IC manufacturing costs (Grochowski, Bhattacharya, Viswanathan, & Laker, 1997). Besides the incidence of its costs Grochowski, Bhattachrrya, Viswanathan and Laker (1997) also underline its importance and indispensability within the whole IC manufacturing process.

A review of the testing process in the semiconductor industry is carried out as follows:

- Approaches to semiconductor testing process.
- Semiconductor testing process steps.

Approaches to semiconductor testing process

According to Marinissen, Iyengar and Chakrabarty (2002) the integrated circuit (IC) testing process is unique because of:

- The physical construction method characterizing the system-on-chips (SOCs). SOCs are in fact constructed "by embedding a certain number of modules (also called cores)".
- The different defect behavior shown by each single module.

Due to the process uniqueness, the testing activities are carried out in several separate and not mutually exclusive manufacturing stages (Grochowski, Bhattachrrya, Viswanathan, & Laker, 1997) and locations (Marinissen, Iyengar, & Chakrabarty, 2002):

- Module testing which is carried out at the module manufacturer site and its characterized by dedicated tests for each module produced.
- System integration testing at the assembler site.

The reasons of such testing approach are twofold:

- "The cost of a failure increases dramatically the later it is detected" (Ntafos, 1998) and therefore it is more convenient to start testing already at the core's producers plant instead of waiting in doing it at the assembler site.
- The system integrator is not able to create high-quality tests because he lacks information about the core's implementation. In fact the core manufacturer does not reveal them due to their confidentiality content. As a consequence, the module assembler can only follow a "divide-and-conquer test generation approach which contains the hard-to-test parts of the SOC to one or few module only" (Marinissen, Iyengar, & Chakrabarty, 2002).

Therefore in the IC's testing process the module test has to be carried out before the module itself is integrated into the circuit. The same concept is also endorsed by Zeng and Ito (2006) stating that "SOC typically contains various predesigned and pre-validated embedded intellectual property (IP) cores" and adds to his analysis that these cores are provided by different core vendors.

The benefits of such testing method are analyzed by Marinissen, Iyengar and Chakrabarty (2002) who identify the following positive effects:

- Shorter test generation run times.
- Smaller test data volume.
- Enabling of test reuse because of its modularity.

Larsson and Peng (2001) analyze the parallel testing possibilities within such a testing environment. In his article the author provides interesting insights and confirms the possibility of testing concurrently different modules' functioning during the system integration tests. Such parallelization though is constrained by the fact that the system undergoing testing shares many common resources, thus inhibiting a full test parallelization.

Another testing approach used in the semiconductor industry is provided by the work of Ravikumar and Kumar (2002). He introduces a complementary testing methodology useful at the system integrator level. The method is a partitioning one. It consists of testing a portion of the circuit while the other parts of the circuit are powered off. According to Ravikumar and Kumar (2002) by testing a core at the time the confidence of the testing procedure is higher rather than setting a minimum acceptable threshold value for the system integration test carried out as a whole.

Last, Zeng and Ito (2006) have introduced another system-level testing approach. The approach introduced is based on the concurrent tests of the different cores embedded in the SOC. The testing methodology is built around three steps:

- Pre-computed test sets from core vendors are merged into a shared test set.

- Scan chains of different cores in one SOC are utilized to construct a scan tree based on the merged test set.
- All cores in the scan tree can be tested simultaneously using only on e test input.

According to Zeng and Ito (2006) the main idea behind this testing policy is the sharing of a test set for multiple modules in order to test simultaneously multiple cores while running the shared test set.

Semiconductor testing process steps

Grochowski, Bhattachrrya, Viswanathan and Laker (1997) in their article analyzes also the major testing steps of a typical IC manufacturing process. Though it is not of interest to detail such a topic with particular relevance to the semiconductor industry we are going to briefly detail it since it includes some testing typologies which have been also observed in the main case study.

The following figure represents the main testing steps during a IC manufacturing process:

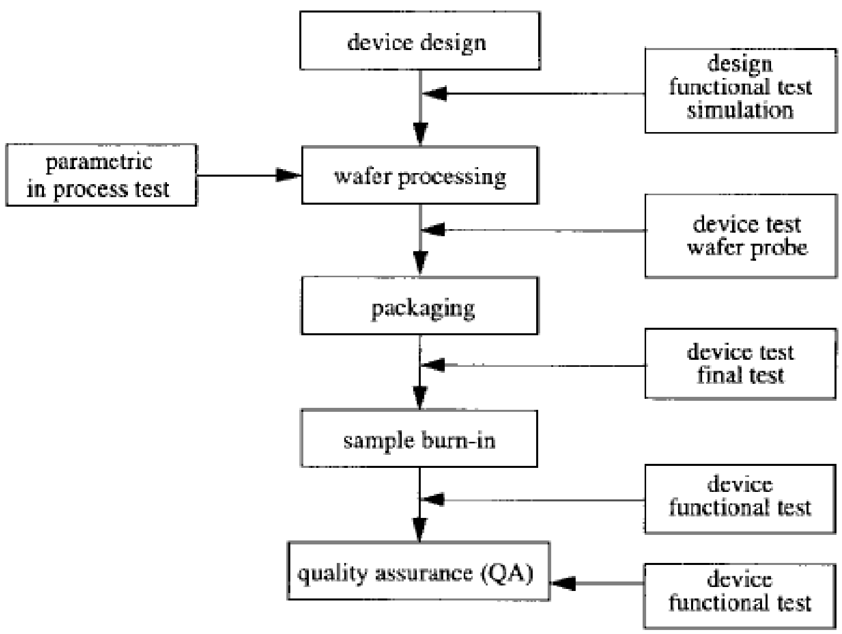

Figure 5 - Major steps in IC manufacturing flow (Grochowski, Bhattachrrya, Viswanathan, & Laker, 1997)

The performed testing are the following:

- Design functional test simulation: it is intended to verify the functionality and the performance of the product.

- Device test wafer probe: it is intended “to identify any major processing defects and to ensure an accurate process control” (Grochowski, Bhattachrrya, Viswanathan, & Laker, 1997).
- “Device test final test aiming at eliminating the devices that fail to satisfy one or more of the expected performance specifications and to ensure proper handling, wire bonding and packaging” (Grochowski, Bhattachrrya, Viswanathan, & Laker, 1997).
- Primary device functional test which consists of stress testing such as burn-in tests.
- Secondary device functional test. This test is performed only on a smaller sample for quality assurance purposes.
- Feed-back chain of failure mode information to the previous steps forming a closed loop control mechanism.

Finally we found of interest to investigate another testing approach, for which, though, there is no academic verification on its applicability on the two previously analyzed industries. On the other hand this approach has been used and has received the academic attention for its application in the consumer electronics industry. Therefore, due to its applicability and relevance concerning our main case study, we thought of interest to investigate on it.

The testing method we are referring to has been discussed by Mujjiga and Sukumaran(2007). Interoperability test aims at validating “entities that are to function as a part of a large system” (Mujjiga & Sukumaran, 2007).

In particular the interoperability testing method “tests the end-to-end functionality in a complete system of multiple devices to validate that they are interoperable” (Mujjiga & Sukumaran, 2007).

Since this test verifies whether a system made up of several components, devices or modules interoperate with each other, we can therefore classify it a system integration testing methodology and reasonably assume that it can be applied to a testing situation where different modules can be identified. The latter conclusion has been drawn through a deductive reasoning by the authors of this Master Thesis and doesn’t find any support on the existing literature. We therefore suggest this can be an interesting area to further analyze.

The overview of testing practices and methodologies in the software development and semiconductor industries provides useful hints on the main policies governing the testing activity, which can be to a good extent generalized.
The trade off time/cost/accuracy of testing appears to be of critical importance when selecting the testing methodology to be adopted. The prioritization of one among these performance indicators can lead to the choice of a more exhaustive testing policy (accuracy as a priority) or a random-based testing (cost or time as a priority).
Test modularity is indicated as a preferential way to address the problem of test sequencing in relation to time reductions. As a drawback, it also brings along the issue of standalone testing and interoperability testing.

2.3 Conclusions

Being the improvement of testing process performances the core of our analysis, it has been of interest to consider the academic work available on both

- the factors impacting on the cost of testing.
- the main drivers guiding the choice of a specific test approach depending on objectives and contextual constraints.

Cost of Testing is one of the principal components of Total Cost of Quality. As such, it is necessary to identify the correct level of investments in quality conformance appraisal that best mediates the trade-off between cost of testing and desired level of outbound quality (Basu, 2004).

The components of Cost of Testing can be identified as fixed costs, recurring costs, production yields, utilization and test throughput. Each of them can perform as a lever in order to reduce the total cost of testing without impacting on the outcoming quality, if targeted with specific actions (Johnson, 2005).

The Cost of Testing is impacted by specific choices of allocation for inspection resources: sampling rather than performing inspection on 100% of production have different impacts in terms of costs, and the choice of either politics of inspection is mostly dependent on the features of the specific product and production system (Vaghefi & Sarhangian, 2009) (Rau & Cho, 2009) (Rau & Chu, 2005).

The Cost of Testing can also be tackled from the perspective of presence of test errors of type I and type II. In order to reduce the propagation of errors along the manufacturing chain, multiple inspection stations are suggested to be placed in correspondence with the strategic manufacturing steps (Kakade, Valenzuela, & Smith, 2004) (Shiau, Lin, & Chuang, 2007) (Vaghefi & Sarhangian, 2009). Keeping more expensive tests downstream of relatively less expensive ones (Shaoxiang & Lambrecht, 1997), and re-testing only rejected items when required (Ding, Greenberg, & Matsuo, 1998) are also suggested as practices with a beneficial impact on the reduction of Cost of Testing.

The overview of testing practices and methodologies in the software development and semiconductor industries provides instead useful hints on the main policies governing the testing activity, which can be to a good extent generalized.

A first relevant outcome from the literature review is the importance for testing to be representative of the actual operating conditions the product/system will be subject to (Harrold, 2000).

The trade off time/cost/accuracy of testing appears to be of critical importance when selecting the testing methodology to be adopted. The prioritization of one among these performance indicators can lead to the choice of a more exhaustive testing policy (accuracy as a priority) or a random-based testing (cost or time as a priority) (Ntafos, 1998) (Weyuker & Jeng, 1991) (Chen, Kuo, Merkel, & S.P., 2004). In some cases it is nonetheless possible to adopt hybrid policies that lead to a good compromise of performance results (Ntafos, 1998). When exhaustiveness of testing cannot be achieved or is purposely not achieved for the above mentioned reasons, a risk arises due to the impossibility of generalizing the positive outcome of tests to the whole system. It is indeed not possible to prove the complete lack of faults in the final product/system, even if all the test procedures do not detect any fault (Harrold, 2000).

A significant part of the literature stresses the relevance of test modularization in order to achieve time savings through parallelization, especially when the testing activity is cumbersome in terms of time requirements (Onoma, Tsai, Poonawala, & Suganuma, 1998). Automation is also indicated as a possible solution, when viable, to ease the testing activity and possibly achieve time savings (Harrold, 2000).

Consequent to test modularization, it appears of relevance the distinction among tests on individual parts of the product/system, and interoperability tests among parts (Mujjiga & Sukumaran, 2007). These last ones require the product/system to undergo testing as a whole since the verification aims at testing entities that do not stand alone but are part of a system.

The importance of sequencing for modular testing is therefore addressed. In some cases it appears to be preferable to anticipate testing as much as possible through parallelization of modules testing, due to the exponential increase of cost of failures the later they are detected along the value chain (Ntafos, 1998). In other cases, mostly when changes in the product configurations are allowed up to as late as in the testing phase, the postponement of testing is preferred (Feitzinger & Lee, 1996).

The necessity of ensuring that no propagation of error takes place during testing appears to be of critical importance as well, especially when combined with tests modularization. This brings along the need of control on the modifications introduced in the product/system after an error is encountered during testing, so that the possibility of new errors generated during the error-resolution phase can be excluded (Onoma, Tsai, Poonawala, & Suganuma, 1998). Some literature suggests that this can be achieved through a centralized control of the modifications required during the test phase (Onoma, Tsai, Poonawala, & Suganuma, 1998).

The findings emerged from the literature analysis can be summarized as follows, with the purpose of considering them within the analysis:

- Some major components of Cost of Testing can be identified; therefore it is of interest to analyze improvement opportunities in the testing process as we defined it by targeting these components.
- Cost of Testing is impacted by the politics of allocation of testing resources, which in turn depend on specific product or production features; therefore it is of interest to bear this consideration in mind when analyzing improvement opportunities in the testing process as we defined it.
- Cost of Testing is influenced by the presence of type I and type II errors arising during the test execution; it is therefore of interest to consider this aspect when analyzing improvement opportunities in the testing process as we defined it.

and

- Testing policies are chosen on the base of performance trade-offs (cost/time/quality). It is therefore of interest to analyze improvement opportunities in the testing process as we defined it on the base of the fit between performance priorities and chosen testing policies.
- Test modularity is indicated as a preferential way to address the problem of test sequencing in relation to time reductions. It is therefore of interest to analyze improvement opportunities in the testing process as we defined it in terms of test modularization.
- Test modularization brings along the issue of module testing and interoperability testing. It is therefore necessary to address this issue in the testing process as we defined it when considering test modularization.

The literature analysis performed allowed us to point out also a lack of existing academic work in some areas where this Thesis Work aims at providing a contribution.

Despite the good availability of research work focused on characterizing a specific test process, or identifying improvement areas for test processes within certain industries, we have appreciated a lack of generalizing work.

A generalization effort is therefore going to be at the base of our analysis, which aims at identifying systematic interventions for the performance improvement of a generic testing process, released from the context of specific applications or industries.

Section 3: Company Case Study.

Abstract

The case study defined as "main case" is focused on the analysis of a manufacturing company whose core internal activities are represented by engineering, software development and testing for a complex modular product.

The content of the case study is based on the analysis performed by the Authors in the context of a project carried out within the company. The main objectives of the project targeted the improvement of process performances, measured in terms of time, cost and quality.

Due to confidentiality reasons it was not possible for the Authors to fully disclose the content of their work in the company within this Thesis Work. Most of the names and figures mentioned during the analysis are indeed fictitious, and the details about the product and the process maps are not disclosed *in toto*.

The section is organized into two main parts.

The company and its business are at first presented, compatibly with the information disclosure constraints above mentioned. The test process optimization project is also introduced.

The AS IS state of the test process within the company is then introduced and discussed. A Value Stream Map is proposed as a representation of the current process. The punctual criticalities identified within the AS IS process are at last presented and analyzed.

3.1 Project introduction

3.1.1 Company and product

The Company's main product is a complex system composed by a set of modules integrated via interfaces that guarantee the system interoperability. The quality conformance of the system in terms of correct performance according to technical specifications is ensured via a testing activity. This can take up to 150%-200% of the time needed for the whole system manufacturing, and therefore represents a critical phase in the company's value chain.

A generic system is composed by a variable number of modules; each module presents both hardware and software parts; these last ones allow the interoperability with other modules.

The manufacturing of the modules composing a system is completely outsourced to a single supplier. The supplier is also in charge of performing a set of tests that can be carried out on standalone modules.

The activities performed within the boundaries of the Company are a set of system integration tests on the whole set of modules, and a final test. The company also keeps internal other two core activities, namely the system engineering and the software development.

The company also manages the supply of critical manufacturing components in behalf of its module assembler, handling both the documental part and the physical motion of supplies from both software and hardware suppliers to the module assembler.

This case study is principally focused on the systems manufactured for the company's principal customer.

Despite the production being generally of the kind Engineering-To-Order, these systems eventually present a certain degree of standardization at the architectural level immediately below the system one. Each system can indeed be composed by a variable number of standardized modules that are chosen from a "standard catalogue"; this limits the possibilities of customization to the possible combination of different modules and the customization of their functional interfaces.

These types of system also present a characterization of the composing modules as either "typical" or "replicas". Whenever more than one specimen of module type is present in the system, one is selected as a "typical", while the other ones become its "replicas". This brings along a significant implication during the test phase performed in-house, since the tests on typicals are supervised by the customers, while the replicas are tested autonomously by the company without need of supervision from the customer (therefore allowing a certain freedom in terms of tests schedule).

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3.1.2 Test Optimization Project

Objectives and description

The project has been launched in January 2010, with expected termination in December 2010.

The project's objectives focus on the improvement of process performances for the most strategic projects managed by the division, which are identified in the specific projects for the main customer.

The desired improvements of process performances are identified in relation with few critical areas:

- Time: reduction of Lead Time in between the project opening and the final customer acceptance.
- Cost: reduction of costs accrued on the project in between the project opening and the final customer acceptance.
- Quality: improvement of quality for all the components supplied and the final system delivered, from a holistic perspective.

In order to understand the scope of the project in terms of sequential phases, we refer to Figure 6, representing the value chain for a generic system.

The project covered the different phases of the value chain over different time spans, due to the limited resources available on the project and the need of carrying out detailed analysis on each phase. The temporal division of the analysis followed the here mentioned pattern:

- Module assembling, electrical tests, application configuration, functional tests and acceptance tests: January-June 2010.
- Material supply: June-December 2010.

The Material supply phase and possible interfaces with the customer are scheduled ahead in time with respect to the first phase since they determine an extension of the field of analysis upstream and downstream with respect to the company, therefore involving the inclusion of the supply chain. This last part, due to reasons of time mismatch with the submission date of this Thesis Work, won't be included in this case study.

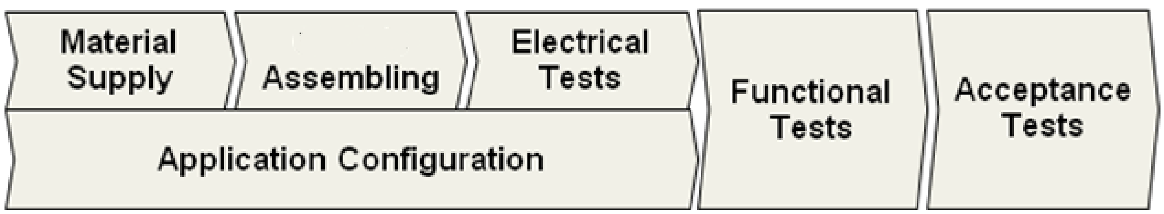

Figure 6 - Product Value Chain

Involvement of the Authors in the project

The Authors took part in the project as external collaborators. As far as it concerns the content developed in this case study, the Authors worked over the period January-July 2010, for about 600 hours. The role attributed to the Authors in the context of the project was the one of project responsible and coordinator for the interfaces among those resources allocated temporarily or *una-tantum* to the project.

As a reference to the organizational structure, the Authors directly reported to the Project Owner, (Project Manager on projects for the main customer), and to a lesser extent to the Project Sponsors (Head of the division of reference and Head of Operations)

3.2 AS IS state

3.2.1 Customer Value Definition and Takt Time

In order to provide guidance for the process optimization initiative, it has been of interest to assess what the customer acknowledges as value, in order to keep it as a point of reference when deciding for drivers of improvement.

We had the chance to brainstorm with the management in the Company and come to an agreed definition of Customer Value as

“An effective, reliable, well-documented system”.

Concerning product families, the scope of the project has been circumscribed, since the very beginning, to the systems for the main customer.

Concerning the definition of a takt time, an accurate analysis of data available lead to the conclusion that is not possible to define a proper takt according to the classical definition:

Takt time = available working time per day/customer demand rate per day.

The obstacle in defining a takt arises with variability of customer demand (Suri, 1998). In our case, the number of orders appears to have been quite steady for the years 2008 and 2010, while it seems to have dropped in the year 2009. Due to the restricted time horizon (because of the recent introduction of the standard) it is therefore not possible to talk about steady volumes of order, nor to identify a trend. Therefore the definition of a takt would have little significance in terms of resource demand calculation.

All the analysis performed on the Value Stream Map (VSM) were therefore carried out considering one individual system at a time as a takt, and identifying those process times that could be considered as standard (either in absolute way or through a multiplicative coefficient) for any system belonging to the product family.

3.2.2 Internal processes

The maps of internal processes represent the analytical drill-down of the process blocks represented in the Value Stream Map.

The process kaizens (elimination of waste at shop floor level (Rother & Shook, 2003)) have been identified through the analysis of processes at the level of process maps in order to identify specific criticalities that would not have emerged considering the process at a higher level of granularity, as in the Value Stream Map.

On the other side, flow kaizens (value stream improvements (Rother & Shook, 2003)) have been identified at the Value Stream Map level, since a higher level of granularity was not necessary for this purpose.

Due to confidentiality reasons, it has not been possible to include the detailed process maps within this section.

3.2.3 Value stream mapping

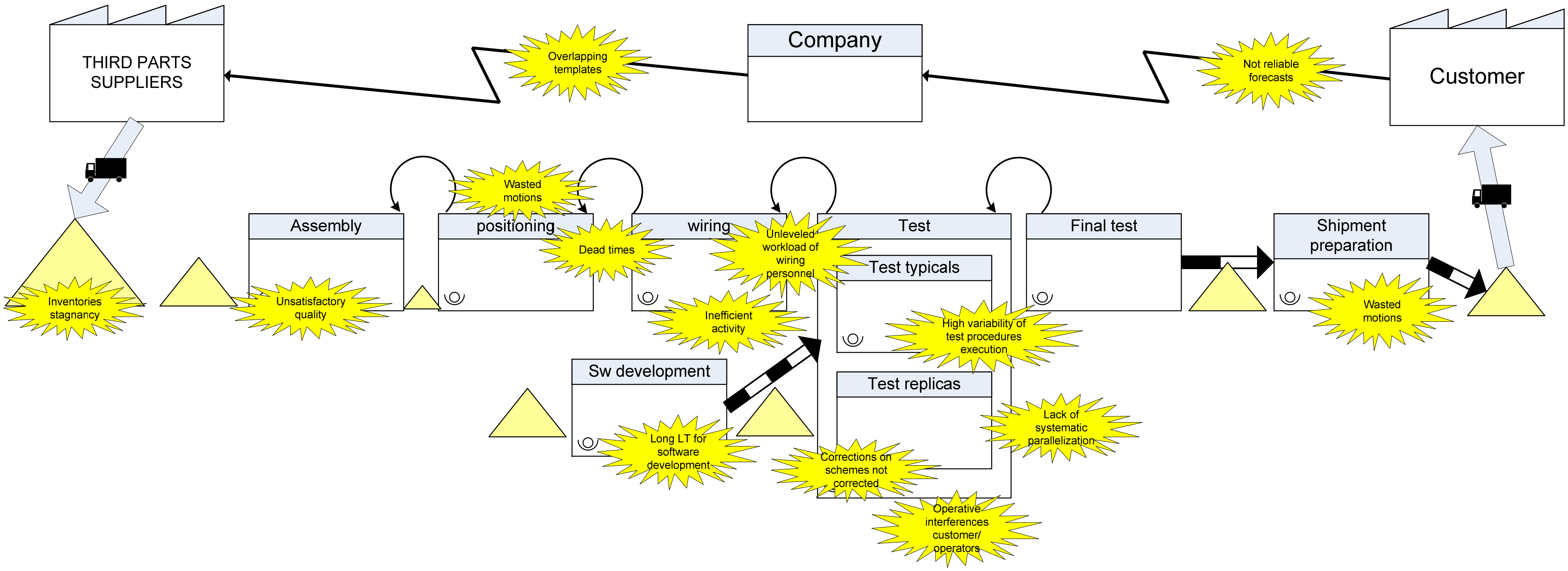

Figure 7 - Value Stream Mapping

3.2.4 Information flow and activity flow

It is possible to identify two parallel flows of activities and information within the defined Value Stream Map.

The information flow is represented by the information exchanged between the customer and the main company, within the main company itself and between the main company and its suppliers.

The information flow under analysis is characterized as follows:

- The customer shares its orders forecasts with the company, according to the following time spans:
  - Forecasts over a three-year period.
  - Forecasts over one-year period.
- The company internally schedules its activity flows.
- The company manages information flows regarding components supplies.

The flow represents the series of activities that are necessary to be carried out in order to deliver what expected by the customer.

The process flow is composed by both activities which add value to the final product and others which do not. A definition in order to discern among these two types of activity can be the following: an activity which adds value is an activity for which the customer is ready to pay for (Womak & Jones, 2007).

The flow of activities in the company is both sequential and parallel and it is characterized by the presence of some buffers where temporary stocks are placed.

According to Figure 7, we can therefore defined two flows:

- Main flow:
  - Assembling activity. Despite this activity is outsourced (as for our definition of testing process) we have anyways decided to consider this activity in the VSM due to the presence upstream of some stocks managed by the company. This allowed us to consider the whole Lead Time, keeping in mind that this activity which is now accounted as internal for Lead Time calculation purposes is going to be treated as external activity in any other further consideration.

  - Inbound activity (positioning).
  - Modules setup (preparation of modules for test activities).
  - Test activity (both on the typical and replica modules).
  - Final test activity.
  - Outbound activity (shipment preparation).
- Parallel flow:
  - Software development activity.

Two scheduling points have been identified, one corresponding with the test activity and another one corresponding with the software development activity, which is scheduled independently from the main flow.

3.2.5 Timeline definition

A timeline was created in order to have a snapshot of the single execution times of every activity within the flow. Rather than knowing the aggregated Lead Time (from order receipt to delivery to the customer), the timeline allows to identify the individual components of this Lead Time split on the activities composing the flow.

Such information allows the company to investigate each single component and possibly understand whether the activity is adding value.

The Test Lead Time has been considered in this case as composed by two main components: Process Time, or time needed for the actual activity to be performed according to standard time, and Waiting Time, due to inefficiencies and variability in the process.

If we consider the total job order dispatching time, the Process Time accounts in this case for generally 25-35% of the total Lead Time for a single system.

Once again, due to confidentiality issues it is not possible to disclose the breakdown of the timeline figure according to the contribution of each activity to the total Lead Time.

3.2.6 Identification of criticalities

We define as criticality "An event whose occurrence has or can have a negative impact on the testing process performances."

The criticalities identified on the Value Stream Map are going to be punctually analyzed in the following paragraphs, beginning from the top-right side of the map and proceeding counter-clockwise.

Unreliable forecasts from customer

The forecasts provided by the customer over a 3-year time span often suffer a systematic unreliability, with gaps in the order of magnitude of ±20%.

This criticality could have a negative impact if:

- The company had set framework agreements with suppliers committing therefore to a certain level of supplies based on the inaccurate customer's 3-year forecast.
- The company had planned an increase in its workforce due to the forecasted workload depending on the number of orders to be received within 3 years.

Overlapping templates

Some processes require the record of information regarding individual systems (for instance the decomposition of the system according to the type of composing modules, or the calculation of components for the manufacturing phase). The information record is manually carried out via standard templates in most of cases.

A specific kind of situation can arise when different actors record the same type of information in their respective templates, therefore implying a duplication of activity.

Inventories stagnancy before assembly and software development

The emission of orders for materials to be purchased for a specific system takes place as soon as the order is confirmed by the customer, regardless of the requested delivery date for the system.

The physical flow of purchased materials, both hardware and software components for the system manufacturing, follows the same path: all materials are shipped from suppliers to the company's central warehouse where their recording in the company's information system takes place. The flow of information related to the stored materials is then handed over to the logistics department.

The retrieval of materials from the central warehouse is triggered in a different moment of the system's lifecycle. The hardware material is needed at the module manufacturer's plant only when the actual manufacture of the system needs to start, while the software material is needed at the testing laboratory only when the software development of the system needs to start.

An analysis of materials flows inbound and outbound the central warehouse highlights a criticality in the AS IS state of the Value Stream Map. Orders are actually placed in great advance with respect to their actual need on their respective sites, therefore implying a certain stock-keeping cost that could be reduced or eliminated by synchronizing the materials inbound flows with the start of the activities they are required for.

Average in-stock time has been calculated as 30 working days for hardware material and 75 days for software material. Stock keeping costs can be calculated as a variable cost depending on the number of shipment order lines: the central warehouse is indeed property of an external company which offers storing, picking and retrieval services at the specified variable cost, which does not vary depending on the stock-keeping period of the stored items.

It is interesting to notice how this stock-keeping cost potentially represents a full loss for the company. A complete synchronization of order emissions so that deliveries from the suppliers coincide with the start of manufacturing and software development activities would indeed completely delete the need for intermediate storage in the central warehouse. This would require materials to be directly shipped when needed from the supplier to the final site of destination (module manufacturer for hardware materials and testing laboratory for software materials).

The current practice of anticipating order placements is preferred within the company because of the way costs and correspondent revenues are accrued.

From a pure financial perspective, this practice represents an early disbursement with an opportunity cost due to premature capital immobilization. Figure 9 represents the timeline of cumulative cost accruals and correspondent financial disbursement for the materials of a sample system (System B). Financial disbursement for materials purchased from the main components supplier takes place on the spot at the moment of material receipt, while other suppliers are paid on an average 90 days basis. The dates of actual requirements of hardware and software material for manufacturing and software development to take place are also indicated.

Figure 9 details the content of Figure 8 with a split view on the cumulative timeline for software and hardware materials.

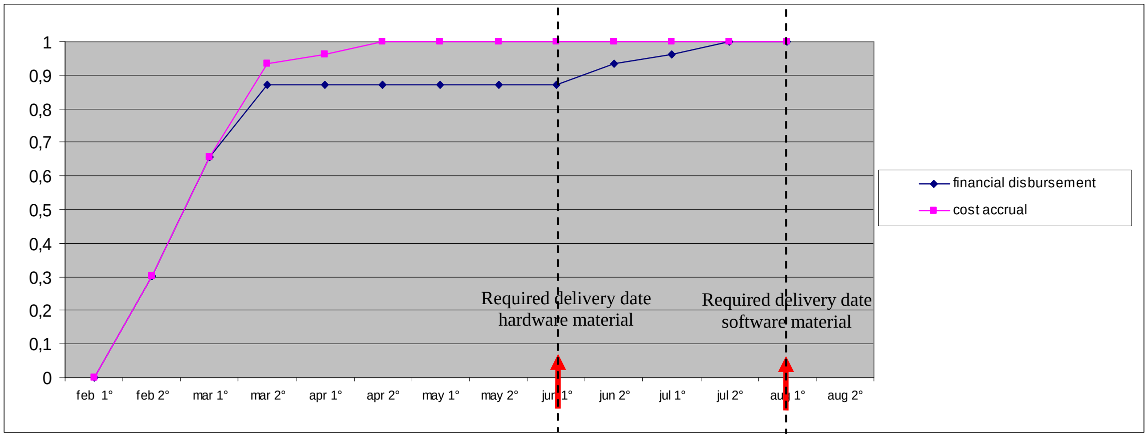

Figure 8 - Timeline of the financial disbursement and cost accruals split for software and hardware materials

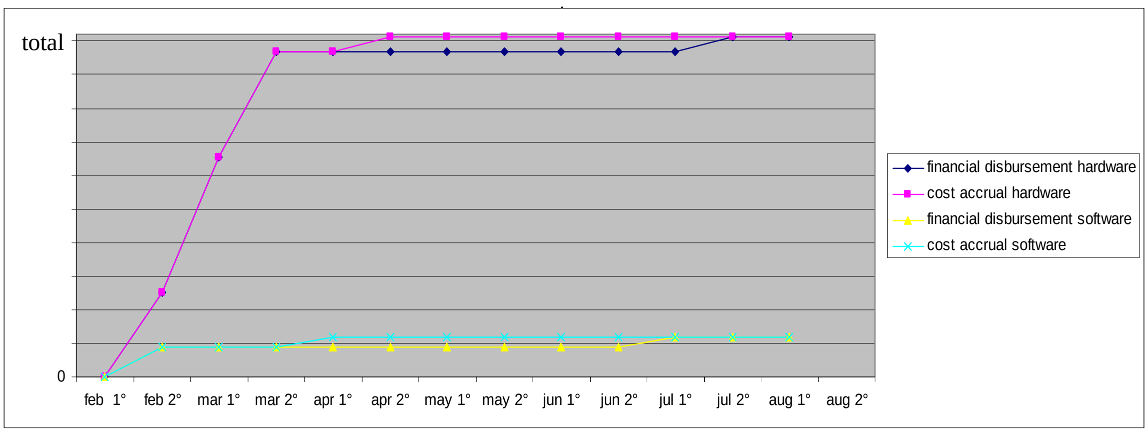

Figure 9 - Timeline of a cumulative cost accruals and correspondent financial disbursement for the materials of a sample system

An analysis of the timelines highlights a consistent stock-keeping period for both hardware and software materials, as already pointed out (average 30 days for hardware material and 75 days for software material). It is evident how both hardware and software material shipments could be arranged so to take place closer to their respective internal due date. Financial disbursements appear to be delayed in time with respect to cost accruals due to the 90 days payment policy with third part suppliers. This delay could be further leveraged by moving the shipment of materials ahead in time, at the expense of cost accrual. Costs are indeed accrued 30% in the month of February, 63% in the month of March and 7% in the month of April, while financial disbursement take place 30% in February, 87% in March, 0% in April, 6% in June and 7% in July.

Ideally, the synchronization of material shipment with their actual need on-site would allow significant benefits due to the shift of financial disbursement windows ahead in time.

Figure 10 and 11 show an ideal situation for the system under analysis, considering shipments for both hardware and software materials synchronized with their due dates on-site. Besides an evident reduction in stock-keeping time (ideally null), the benefits from the financial standpoint is evident. In this case, financial disbursements are shifted 3 months ahead in time, 86% in June, 7% in August, 4% in September and 3% in November.

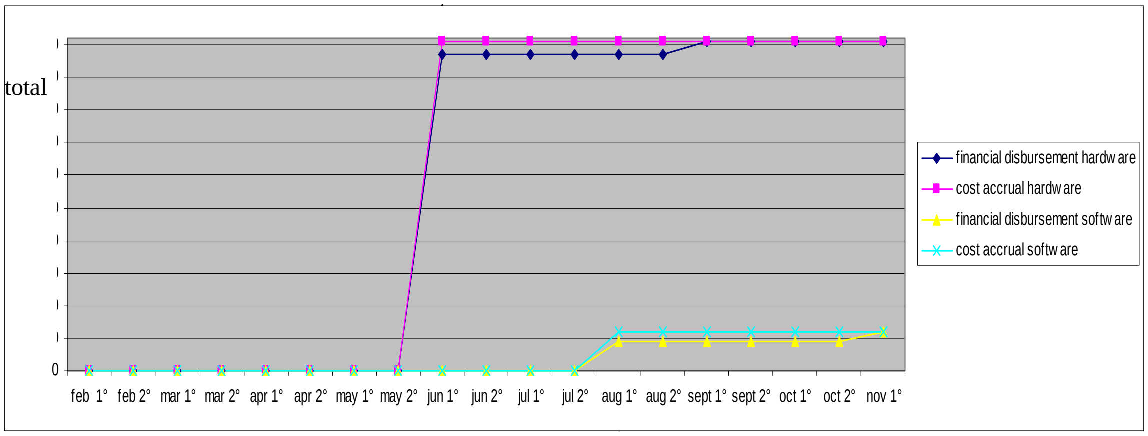

Figure 10 - Ideal timeline of a cumulative cost accruals and correspondent financial disbursement for the materials of a sample system

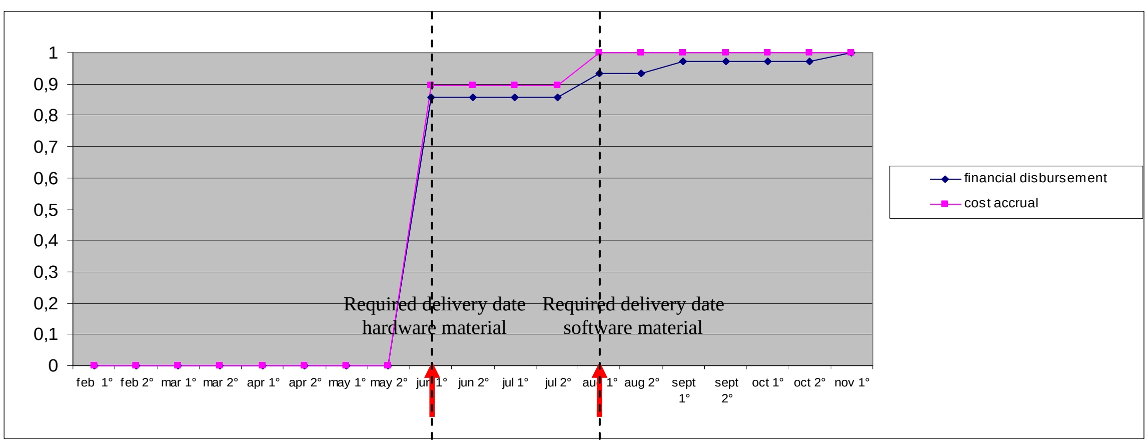

Figure 11 - Ideal timeline of the financial disbursement and cost accruals split for software and hardware materials

Unsatisfactory quality from assembly

The module assembler formally agreed to conform to a quality control plan which includes several types of quality checks. These include:

- Mechanical tests

- Electrical tests
- Capacity and continuity tests
- Functional tests
- Corrective actions.

On the other hand, Company records the occurrence of several quality non conformities in almost each job order. The non conformities are then repaired either by the company's wiring personnel or by the module assembler's personnel that comes on-site.

Concerning the reasons for poor quality, two causes have been identified:

- Inaccuracy in the execution of the tests.
- Quality control plan procedures are not complete.

A comparative analysis of the type of non conformities recorded and the type of quality checks to be performed highlights the possibility that the quality control plans have been at least partially not followed.

On the opposite, the quality check form the supplier fills after the completion of quality checks would indicate the correct output of all the tests performed. It is therefore possible to conclude that:

- Tests are not performed in full accomplishment of contractual clauses by the supplier.
- The misalignment between the quality level indicated on quality control plans and the actual level of quality on the received modules has not yet been systematically tackled within the company.

Wasted motions in positioning

The direct observation of positioning activities on a few systems has led to the identification of some points of deficiency for the process. These are, namely:

- **Multiple module motion.** The inbound receipt of modules prior to placement involves multiple motions before the module is actually placed. At first, the module is unloaded from the truck and positioned randomly in a buffer area where unwrapping operations take place. Only in a second moment, after all the modules have been positioned in the buffer area and unwrapped, the wiring operator gives indication on what module to retrieve from the buffer area and transported in the actual testing laboratory, according to a predefined sequence. The presence of this multiple motion is due to a decoupling point in the flow of modules from manufacturer to testing laboratory. The concept of system with a predefined layout is indeed an input for the module placement phase, while the whole system is treated as a group of individual modules in the upstream phase, both at the manufacturer's site and during the transportation. This origins a decoupling point in the physical flow of modules, determining the need for a buffer area and a multiple motion, respectively non-value added utilization of space and time.

- **Non-value added set-up operations on modules**. The current practice of module set-up prior to positioning includes the operation of removing part of the external protective structure. This operation is identified as necessary by the operators due to space constraints in the testing laboratory.

Dead times between positioning and wiring

During the arrival and positioning of a new system, the wiring personnel supervises the unloading and positioning activities. This responsibility is already attributed to the transportation company, while the wiring personnel is a resource allocated to other specific tasks that do not include supervision. We can consider this as control redundancy.

The impact of this criticality is twofold:

- Cost involved: cost of the time the wiring personnel dedicates to this activity.
- Time loss: the time needed for the supervision of modules positioning prevents the wiring activity to start as soon as each module is positioned, creating a delay in the chain of activities on that branch of the value stream.

Inefficient wiring activity

The wiring activity indicates wide room for the application of 5S and SMED methodologies. The process presents an overall low level of standardization, being allocated to a single person.

The standard times for wiring activity include both time needed for the actual activity to be carried out and a certain number of time losses.

The major sources of time losses have been identified in:

- Entangled wires.

- Usage of obsolete tools for performing activities.
- Creation of shunts for operating equipment that requires powering at specific voltage.
- Disarranged storage of operating equipment.
- Not ergonomic operating space.

A reduction of the standard times for wiring activities could allow the reduction of the cost of test set-up.

Unleveled work of wiring personnel

Figure 12 represents the wiring personnel (one person) workload over a time span of six months; all the considerations have been made on the available Gantt personnel schedules. It is possible to notice the uneven workload distribution over the time span considered.

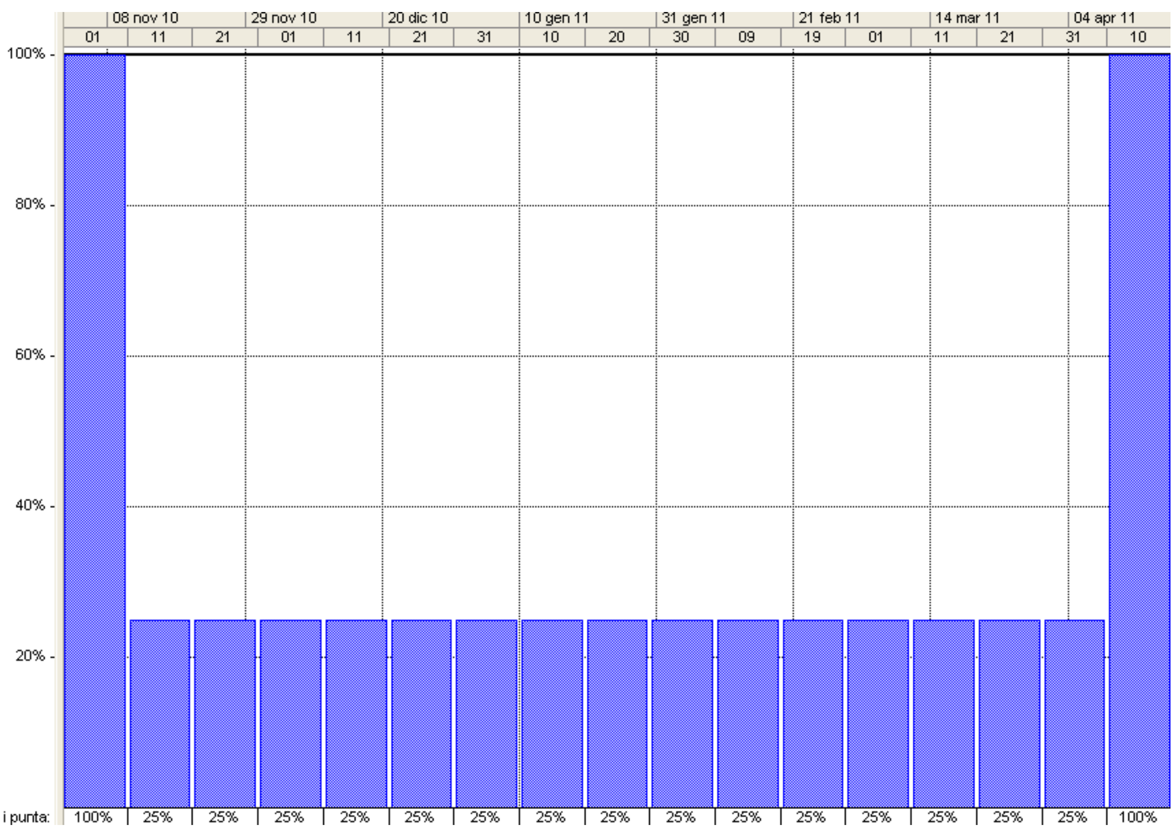

Figure 12 - Wiring personnel workload on one system

The wiring personnel performs the following activities:

- Modules positioning supervision (not included in the tasks assigned, as already mentioned).
- Modules wiring.
- Troubleshooting wiring errors during testing.
- Modules shipment preparation.

In particular, during modules positioning, wiring and shipment preparation, the resource is 100% saturated. During tests performance, the resource is saturated roughly 25% of its available time, and allocated to troubleshooting wiring errors and implementing corrective actions when needed.

If we shift such an analysis on a timeline basis, we can observe that the wiring personnel is completely saturated during some phases of the modules "lifecycle" within the testing laboratory (i.e. inbound transportation, positioning and setup, outbound transportation) while this resource is mostly idle (25% saturation) during the tests phases.

Last, it is important to notice that the uneven distribution of workload for this resource could also present peaks of work overload; this can happen in case two systems are scheduled for concurrent arrival at the testing laboratory, therefore both requiring 100% allocation of this resource for inbound and setup activities.

Long Lead Time for software development

Concerning development logics, the three software components can be developed concurrently to a certain extent, as shown in Figure 13.

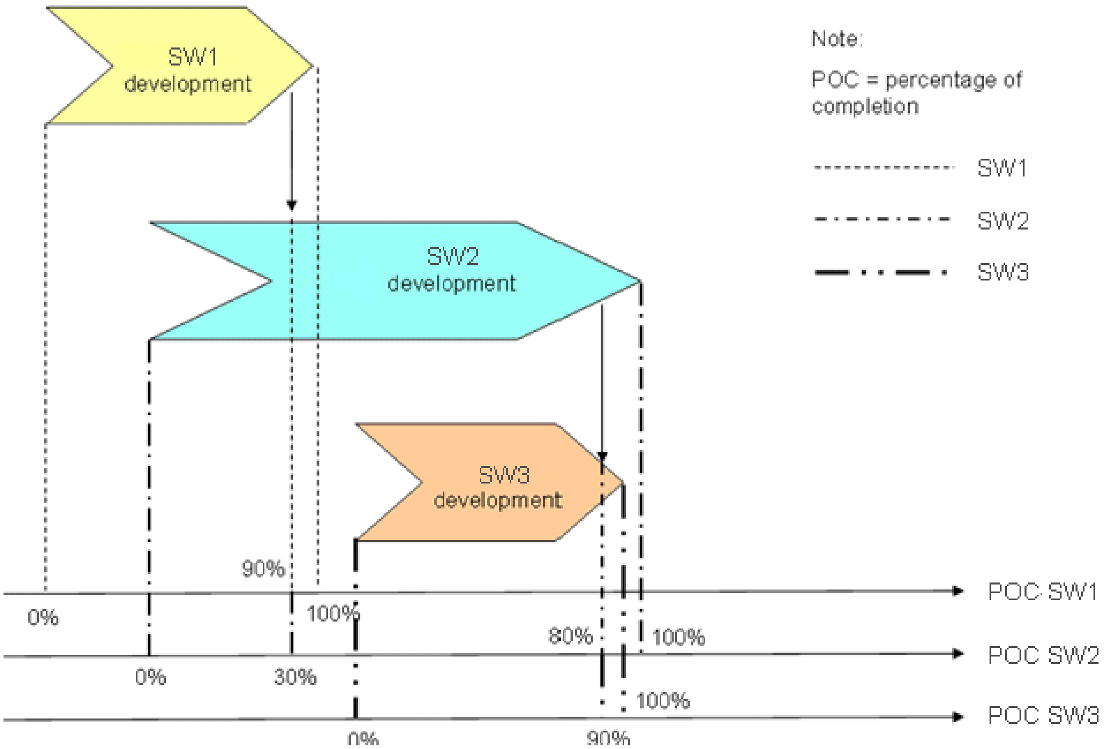

Figure 13 - Software development process

Company currently allocates both internal and external systems engineers to its software development activities.

The allocation of resources appears to be done according to the following logic:

- Type A resources (highly skilled) allocated to supervision of software development process for all the incoming systems, SW1 development, final test and specific interventions on error solving.
- Type B resources (adequately skilled) allocated up to saturation and constantly saturated over the considered period to the routine development of SW1 for some of the incoming systems (initial training on simple systems), SW2, SW3 for all the incoming systems.
- Type C resources (adequately skilled) allocated on demand to chase the peaks.

Also, the software development personnel are allocated on-demand to specific systems after the beginning of the tests whenever software errors are detected or the customer requires extra tests.

Despite a good overall saturation of resources (over a considered sample period of six months, 100% for both internal and external resources), some criticalities emerge with respect to the allocation of resources on the incoming systems.

- The work of systems engineers appears to suffer of frequent interruptions due to
    - Customer’s specific requests on other systems undergoing testing that require a systems engineer to intervene.
    - Error fixing activities on previously developed software that generates errors.
    - Scheduling of activities that cause switching from the development of software for one system to another one.

  This causes the time needed for software development to be 20 up to 45% longer than its standard time.

- With reference to the opportunities for parallelization of software development activities on the three modules SW1-SW2-SW3, the maximization of this parallelization is normally not achieved.

  The benefits deriving from maximizing software development parallelization could be identified in the allocation of a minimized “time slot” across all the resources available. This would guarantee a shorter LT for each single software development and higher schedule flexibility.

  As an example, we can consider the software developed over the period October-January, as depicted in Figure 14.

  The light purple color indicates development activities on system E.

  The dark purple color indicates development activities on system C.

  The orange color indicates development activities on system D.

  The grey color indicates other activities.

  The three parallel sequences represent the schedule of activities for the three systems engineers.

The LT for the system C resulted to be 130 working days, while for E 160 working days, against a standard processing time calculated as 70 days for C and 140 for E. The two resources developing most of the two software are not exclusively dedicated to this activity, as the allocation of 40 working days to a third system (D) demonstrates. A third resource is allocated to the systems for 40 working days.

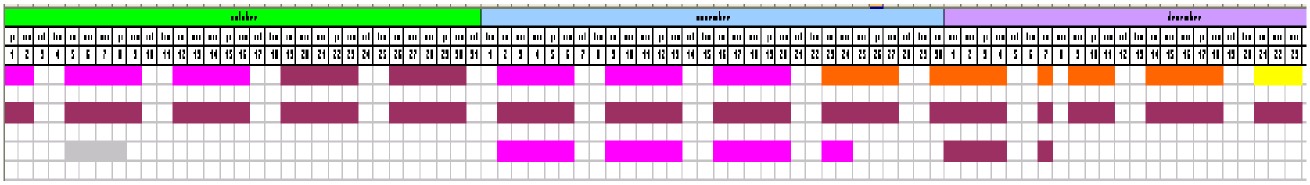

Figure 14 - Software development Gantt chart for the period October-January

High variability of test procedures execution

The total Lead Time variability of tests execution can be split in two components:

- LT variability due to not standardized execution of test procedures.
- LT variability due to the presence of the customer supervising the process for typical modules.

Non standardized execution of testing procedures

The punctual execution of procedures as they are provided to the testing personnel would guarantee a constant LT. Variability is nonetheless implied in the process through:

1. Interferences due to shared resources. The need for accessing shared resources on the system during the execution of tests procedures implies waiting times whenever the resource is in use by another test operator.
2. Interferences due to concurrent testing of multiple modules; it is the case when testing one module can cause disruption in the correct execution of tests on the other modules.

Within the general structure of a testing procedure, some of the tests carried out are identified as generating interferences under the mentioned conditions, while some are not.

It is therefore not possible to concurrently carry out any of the categories of tests that generate interference, while it is possible to concurrently execute all the others. The possibilities of maneuver given by this type of parallelization are anyways limited, considering the preponderance in number and required time (30% of time needed only by a single class of tests) of the types of tests whose execution generates interferences.

3. Non-standardized operative practices among test personnel. It has been acknowledged how the procedures in place for testing do not provide whole coverage for the testing process. There is indeed wide margin for individual operative choices (for instance regarding the usage of operating equipment, or the error-solving practices). This often implies sub-optimal operative choices, lack of best practices spread, and duplication of activities.

   This has been acknowledged as the cause of around 30% of extra times usually incurred beyond the standard time required by the strict procedures execution.

4. Occurrence of errors during testing. The impact of errors occurrences on test LT has been estimated as possibly increasing standard execution times of single procedures up to 500-600%.

Presence of the customer supervising the tests of typicals

The presence of the customer during the tests of typicals brings along a certain variability in the testing LT for these modules, due to frequent cross-checks of output results and requests for additional tests to be performed besides the standardized ones included in the procedures manuals.

Definition of tests execution times

Given the above discussed individual elements that introduce variability in the process, it is possible to give an estimation of their impact on the LT of the test activity.

We define as "best case" for test standard times (per module) the time required by strict execution of procedures in the absence of interfering conditions 1., 2., 3. and 4. Analogously, we define as "real case" for test standard times (per module) the time required for the execution of procedures in the presence of conditions 1., 2., 3., as in reality happens. The occurrence of condition 4. brings along a significant variance that would make an estimation of a real case execution time not significant, and therefore it has not been taken into account for the calculation.

The gap between best case and real case appears to be in the order of +100% in the presence of interferences. The incidence of the presence of the customer during tests on typicals has been estimated as another +50% of the best case per module.

Correction on schemes not implemented

It has emerged as a criticality the fact of the module assembler performing its assembly activities on the base of uncorrected schemes. It indeed happens that corrections are implemented on hard copies of schemes during tests executions whenever an error related to schemes is detected. The implementation of these corrections on the software copy (retrieved and used for the manufacturing of new correspondent systems) can sometimes take place with a certain delay from the actual correction of the hard copies; there has indeed been occurrence of modules for a new system that have been manufactured on the base of not up-to-date schemes. The delay in the implementation of corrections can be traced back to two causes:

- Poorly coordinated mechanism of information sharing.
- Inaccurate and not timely implementation of the corrections.

Operative interference between customer and operator on tests

The physical layout for each system is designed on the exclusive basis of a few technical requirements of proximity among certain types of modules.

Given the respect of these constraints, there is currently no optimization criterion that further drives the layout definition for a system.

One criticality that has been identified in the current system layout is the operative interference brought about by parallel test of typicals and replicas in the same system. It is indeed common to witness operative conditions where the customer, together with a test operator and a systems engineer, works on a typical while another test operator carries out the tests on a replica in the same aisle. This results in a series of operative interferences that worsen working conditions and possibly slows down the pace of testing activities.

Figure 15 shows the layout for one of the systems undergoing testing. Typicals and replicas are differentiated in the scheme; it is evident the non-separation of typicals and replicas in the same aisle.

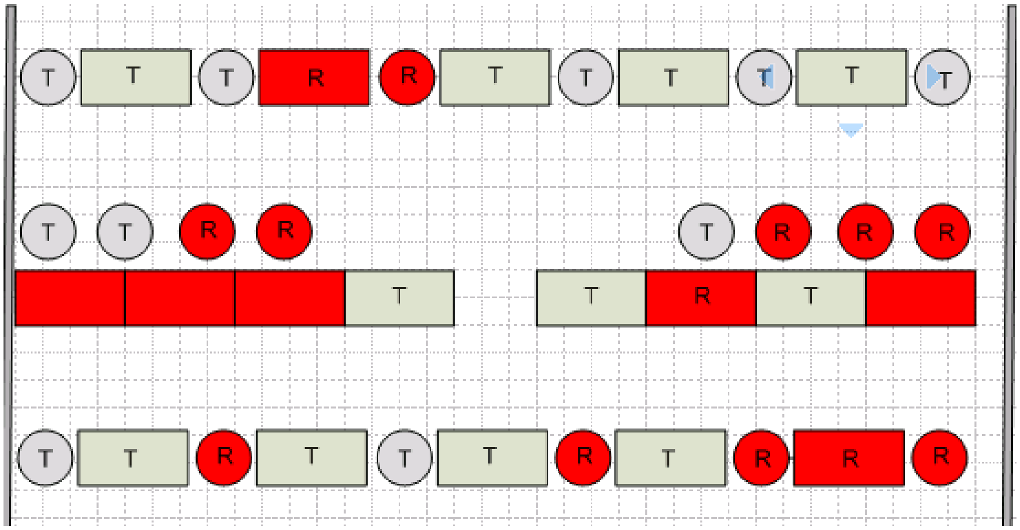

Figure 15 - Layout of a system undergoing testing

Lack of systematic parallelization in tests

As already mentioned, among the modules constituting a system, some are considered as typicals and the remaining ones are considered as replicas of the correspondent typical.

As for contract clauses imposed by the customer, tests must start from the typical modules. Tests on replicas cannot therefore start before the correspondent typical has started.

Figure 16 represents the allocation of resources on systems concurrently undergoing tests over the period October-November.

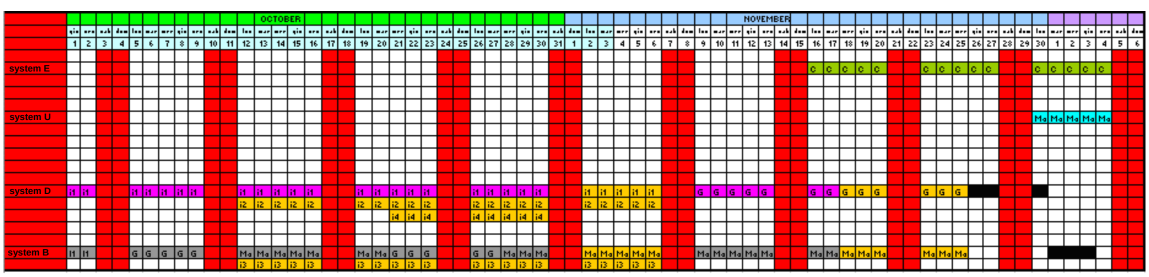

Figure 16 - Gantt chart for the allocation of resources on systems concurrently undergoing tests in the period October-November

The systems undergoing tests in this period are:

- E (status: ongoing)
- U (status: ongoing) not considered further due to lack of data

- D (status: completed)
- B (status: completed).

The orange color wants to indicate tests activities on the replica modules in all systems.

The black color represents the days dedicated to the final test in all systems.

A reference to the operator working on each system is also indicated on each system.

The total testing Lead Time for the systems under analysis are:

- D: 90 working days
- B: 80 working days.

It is possible to notice a lack of systematic parallelization in the test activities. In order to support this hypothesis we can perform a qualitative systematic parallelization on the same systems. The results obtained are showed in Figure 17.

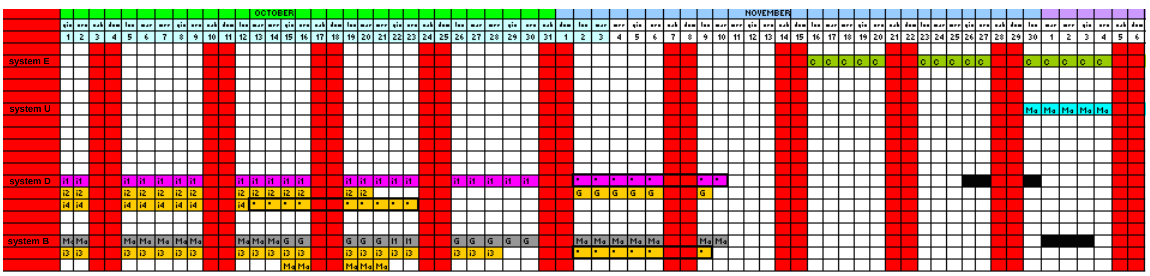

Figure 17 - Gantt chart deriving from an optimal resource and testing allocation

The total testing Lead Time is now:

- D: 60 working days (- 30%)
- B: 60 working days (- 30%).

These results can be achieved considering the availability of an additional external resource for those days highlighted with a black frame in Figure 17.

It is important to notice that testing personnel is currently mostly external, therefore the need for an extra resource, given its availability, does not imply the need for the permanent addition of extra capacity.

Wasted motions in shipment preparation

The process inefficiencies already discussed for the positioning activity have direct repercussions on the shipment preparation phase.

The external structure that has been removed during positioning has to be re-positioned before shipment takes place. This implicates, analogously as the removal activity, non value-adding time.

Poor end communication with the customer

This criticality aims at identifying a systemic problem more than a local one.

It has happened in the past cases where the systems were ready, the tests had a successful outcome, but the customer was not willing to accept the delivery of the system at the contractual date due to internal reasons.

This highlights the need for a more efficient communication between the company and its customer.

Company could indeed benefit from a more efficient communication in terms of more accurate planning for external resources; this would allow avoiding the anticipation of demand and consequent disbursement for materials and external personnel.

It is important to highlight that this might represent a criticality on the customer’s side as well; the customer faces indeed the need of scheduling supervisors’ activities for tests on-site at Company’s, and a more efficient communication would benefit a more even distribution of workload.

Section 4: Company2 benchmark

Abstract

A second case study is presented within this section. This second case is focused on analyzing the testing process in a company whose core activities are analogous as the ones presented for the main company. The company operates indeed in the same industry as the main one. We can therefore consider this as an intra-industry benchmarking.

The section is organized into two main parts.

The company and its main processes are at first presented, compatibly with the information disclosure constraints above mentioned.

The test process and its main activities, along with the logics that regulate them are then discussed.

The same confidentiality restrictions applied to the main case apply to this second case study as well.

4.1 Company and product

We consider the production of systems presenting analogous characteristics to the ones manufactured by the previous company.

The company's core activities are identified by the three following processes:

- Software development tailored on the specific system requirements.
- System engineering tailored on the specific system requirements.
- Testing the systems as a whole.

In Company2 the tests are performed at the module assembler's site; therefore also setup activities are carried out at the supplier's site.

Each system differs from the others concerning its particular specifications. Company2 operates with multiple customers, both on a local and on a global scale.

This leads Company2 to consider every order as one-of-a-kind concerning the software developments and engineering activities. As a practice, Comapny2 contractually defines during the negotiating phase with its customers the testing procedures that are going to be performed. Every deviation from the standard testing procedures requested by the customer needs to be evaluated at the time the order is being negotiated. Once the testing procedures are all identified, the system delivery time is accordingly defined. This way of conducting business allows Company2 to avoid any finished goods inventory warehouse once the system is terminated.

It is not possible in this case to define a fixed system lead time, since it can vary significantly from system to system depending on the specifications.

4.2 Testing process

In Company2 all the activities performed, apart from engineering, are differentiated and sequentially performed depending on whether a module is a typical or a replica.

Once the engineering work has been carried out on the whole system, both the software developers and the module assembler start working on tailoring the software modules of the specific typical modules and on assembling the typical modules, respectively.

Once these two activities have terminated, a pre-test activity starts. The pre-test activity can be considered as the test activity described for the main case study, with the only difference that the customer is not present. During this period, whose length has been defined with the customer depending on the type of tests it has required Company2 to perform, the test operator along with the systems engineers test the correct functioning of the system's typical modules. In this pre-test with only the typical modules that are preset in the testing area is not possible to verify the whole system's procedures, therefore only a partial test in carried out.

Once the pre-test is finished, the actual test starts. The test activity differs from the pre-test activity only for the presence of the customer in the testing laboratory. During the test activity the company's testers just perform a limited part of the testing procedures. This part constitutes the total number of procedures the customer wants to verify to be able to accept the system as correctly performing according to the quality standards defined. The objective of this test is indeed getting the customer approval that the typical modules are conform to quality requirements.

At this point, the replicas are assembled and subsequently tested (Figure 18). The pre-test activity for the replica is less time consuming that the same activity for the typicals because it involves copying the software already developed and tested on the typicals and testing the functioning of only each single replicas.

At the end, every module, both typical and replica, is delivered to the customer. The equivalent of the final test for the first case study analyzed is here performed at the customer's site.

The whole system test is performed by the same team of experts who have worked on the same system during the pre-test and test at the modules assembler site.

The following figure aims at graphically representing the sequence of activities as they are carried out in the company and the corresponding actors involved.

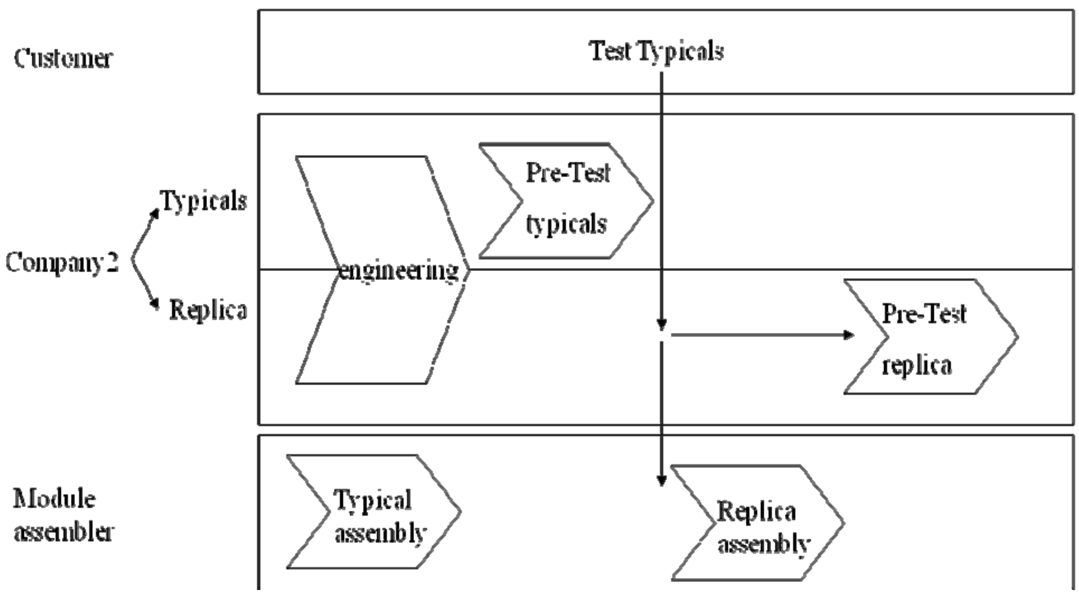

Figure 18 - Company2 testing process

This figure does not intend to represent the physical site where single activities are carried out. The activities are indeed performed either at the supplier's site or in-house according to the following scheme:

- Activity performed in-house:
  - Engineering
  - Software development.
- Activity performed at the module assembler's site:
  - Assembling

  - Pre-test typical modules
  - Test typical modules
  - Tre-test replica modules.
- Activity performed at the client's site:
  - System integration tests.

Section 5: TETRA PAK benchmark

Abstract

A third case study is presented within this section. This third case is focused on analyzing the testing process in TetraPak packaging solutions (Modena, Italy). The company operates in the food packaging and processing industry and the plant under analysis represents the corporate hub for the testing of filling machines.

The section is organized into four main parts.

The company and its business are at first presented.

The test process and its main activities, as they are carried out within the company, are then introduced.

The characteristics of the World Class Manufacturing implementation within testing are then discussed, with particular focus on the logics regulating the testing process.

The main KPIs for the testing process are then introduced, with a comparison of their trends before and after the implementation of World Class manufacturing within testing.

5.1 Company and product

Tetra Pak, part of the Tetra Laval group, is a Swedish company operating in the business of integrated solutions for food processing and packaging. The company is currently operative in 165 countries worldwide and creating revenues for 8.955 million Euros as for 2010.

The core product categories can be identified in food packaging materials, food processing equipments, filling machines and distribution equipments. A series of additional services are also provided so that it is possible for the company to compete in the penetrated markets offering complete food packaging solutions.

The company’s plant situated in Modena (Italy) is the focus of this presented case. Tetra Pak Modena is the second biggest site after the Swedish headquarters in terms of number of employees, but the first production site in terms of number of filling machines produced. Currently the product range counts on 3 different models of filling machine (TPA3/Flex, TPA3/Speed and TPA3/CompactFlex) which represent 70% of all the filling machines produced. Testing is indeed the central activity in this plant, which collects pre-assembled modules from external suppliers and performs internal tests before proceeding to the shipment to the customer's site.

Figure 19 - Filling machine of type A3/Flex

The specific structure of a filling machine can vary depending on the model, but a basic common structure can be identified across all models (with reference to TPA3/Flex, TPA3/Speed and TPA3/ComapctFlex). A single machine is composed by 6/7 separate modules that are mutually interconnected via electrical and mechanical connections. The machines work with two main input materials, which are the paper (called packaging material) used to produce the actual package and the liquid nutrients that have to be packaged. The packaging material is loaded onto the machine in form of a roll. A two-rolls slot is present in the machine so that two rolls can be loaded at the same time; this means that setup operations can be carried out with no need for the machine to stop, since a mechanism automatically shifts the machine feeding to the second roll once the first one is over. The packaging material web passes through a module where a thin strip of polyethylene is applied on its edge in order to seal the package longitudinally and meet packaging sterilization requirements. Afterwards the packaging material passes into a peroxide bath to be sterilized. A forming section creates then a continuous tube where the injection of nutrients takes place. The confluence of liquid food in the machine is allowed by system of internal piping. Once the packaging material tube has been filled with liquid, a second and a third induction sealing is made so to seal up and cut the paper tube transversally. This creates individual filled and sterile packages which then undergo the final forming module where the package flaps are folded and sealed with hot air in order to get to the final shape of the package.

Filling machines are usually integrated within a line, so that at their output extremity one can usually find a conveyor belt connecting the machine with the subsequent distribution equipments.

Figure 20 represents the typical structure of a complete line, with a possible pre-treatment station (for instance for dairy products), a filling machine, an accumulator, and add-ons equipment (straw applicators, cap applicators, film wrappers or others).

Figure 20 - Typical structure of a complete line

5.2 Testing process

The testing process in Tetra Pak takes place in a dedicated workshop where between 20 and 25 machines can be placed at the same time for testing operations. The workshop is conceived to host under regular operating conditions 20 machines at the same time, while the seven remaining slots are usually allocated to the R&D department for particular machines used for development purposes. These seven slots can be under exceptional demand conditions allocated to machines to be tested, and they can therefore perform as buffer capacity.

The testing department counts on 50 total employees, of which 35 Test Engineers and 15 Engineers divided into Planning (4 people), Quality (4 people) and Production Engineering (7 peoplee involved in resolution of problems encountered on machines during testing and improvements or debugging on the simulator used for testing at the supplier's site). External temporary workforce is employed during peak times for the more manual activities such as machine assembly and disassembly.

The sequence of activities taking place during the testing process can be summarized as in Figure 21.

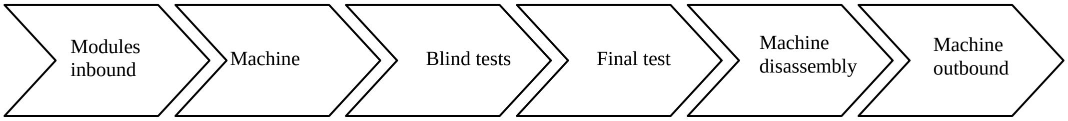

Figure 21 - Testing process value chain

- Modules inbound. All the modules composing a machine are received at a synchronized time at the shipment dock.
- Machines assembly. The different modules composing a single machine are moved to the allocated slot in the workshop and mechanical plus electrical connections are created across modules. This takes under current conditions about 3 working days.
- Blind tests. Specified tests are performed on the machine according to predefined procedures.
- Final test. The machine undergoes a final test consisting in a production run simulating complete production conditions.

The time needed for blind tests plus final test under current conditions is about 14 working days. The testing phase is aimed at ensuring the correct functioning of the machine, therefore a series of errors can be encountered during both blind tests phase and final test phase. The types of errors that can be encountered can be classified in the following categories:

- Suppliers' quality faults on modules (currently account for 50% of all errors encountered).
- Wiring errors.
- Engineering issues.

- Machine disassembly. The machine is disassembled into the composing modules and cleaned up for shipment. This takes under current conditions about three working days.
- Machine outbound. The modules are moved to the shipment preparation area where they undergo shipment setup with application of protective wrapping and storage in a determined type of case depending on the chosen freight vehicle.

5.3 World Class Manufacturing in testing

Being the testing process the core activity in Tetra Pak plant in Modena, the Lean implementation, through the WCM (World Class Manufacturing) project, widely impacted it under many aspects

5.3.1 Production takt

The testing workshop works on a takt time, which has been calculated for each of the three families of products corresponding to the three machine models tested as being 1,5 machines/week for model A, 1,5 machines/week for model B and 2 machines/week for model C. These takt times are periodically revised so to make sure they reflect the market demand.

5.3.2 Workload level

The scheduling of activities for the 35 test engineers is done on the basis of “machine ownership”. Everyday between 8 a.m. and 9 a.m. the new modules reach the receiving dock at Tetra Pak Modena’s plant, and the first free test engineer is allocated to the new machine as a machine owner. The test engineer remains allocated to the same machine until all tests are completed, and becomes available again when his machine is ready for shipment.

The 35 test engineers represent the internal testing resources. Whenever peaks of work are expected because of variations in takt time or other particular conditions, the internal capacity is fully allocated to the core activities of testing (as above mentioned, all activities are considered as core excluding machine assembly and disassembly). The peaks are managed with the request of temporary external personnel which is allocated to more manual activities (machine assembly and disassembly) in order to cope with the demand peak.

5.3.3 Lean Supply Chain

Testing in Tetra Pak Modena relies on a Lean Supply Chain for the process to be carried out as it currently is. The “gears” of transmission of WCM to the Supply Chain can be identified in the following points:

- Transmission of takt time to suppliers. The takt times that set the pace for the testing activity, as above mentioned, are transmitted to the first tier suppliers of the modules composing the machine. The modules of a certain type of machine are required to be shipped at the receiving dock in a specific time frame everyday (from 8 to 9 am every morning). The modules to be shipped within an individual shipment are the ones required for the composition of the machine type demanded by the takt for each specific day. The collection of modules from suppliers takes place on a “milk run” basis, involving one transporter picking from each and all the suppliers the modules required to compose one machine of a specific type. As for visibility, the suppliers are given two up to six weeks to adapt to new takts whenever these are recalculated.

- Full visibility from suppliers. The first tier suppliers are required to make their production plans available to Tetra Pak one week in advance from the actual plan to be implemented so to allow full visibility and an optimized schedule of pick-up runs, as mentioned in the point above.
- Supplier relationship growth. The first tier suppliers are managed in a partnership-oriented perspective. Framework agreements are in place with these suppliers so to guarantee a certain stability of the commercial relationship from both sides. Strict requirements are then applied from Tetra Pak to guarantee the minimum level of supplier performance that allows the Lean process to run smoothly. As an example, these suppliers are required to guarantee a maximum of twelve days of Lead Time even if their internal Lead Time is higher. On the other side, the company invests in suppliers’ growth and in the empowerment of the relationship through the sustaining of suppliers in adapting their process to the standards of WCM. It is usual practice indeed for Tetra Pak to send its technicians on site at the supplier’s plant in order to assess criticalities in the processes and providing support for improvements on the base of the solid experience that the company has matured within WCM.
- Free-pass module tests. Figure 22 depicts the complete testing process of a machine as carried out along the whole supply chain. The block named “internal testing” represents the sequence of activities performed internally in the testing workshop as explained in Figure 21.

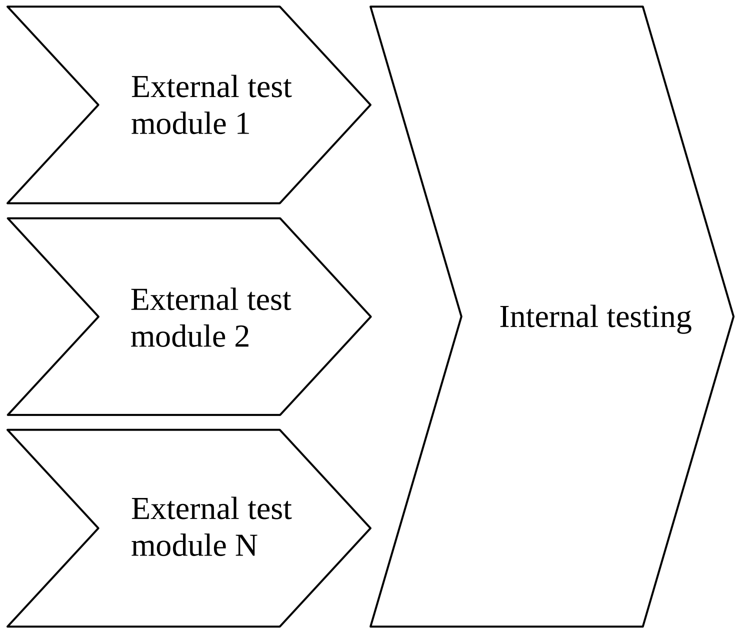

Figure 22 - Testing process of a machine as carried out along the whole supply chain

The modules manufacturers (first tier suppliers) are in charge of testing the single modules they manufacture on behalf of Tetra Pak. The testing of individual modules, part of a machine, is made possible by a simulator device that is connected to the individual module and that simulates the presence of the other composing modules (from the logical and mechanical standpoint) so that no alarm is generated by their physical absence. This practice of externalizing a part of the testing process on the individual module has been adopted by the module manufacturers upon explicit request of Tetra Pak, which has also provided the simulator device that makes possible this operation to take place.

- Collaborative problem solving. The relationship with the first tier suppliers presents both a traditional aspect and a more collaborative one. Whenever an error is encountered during the testing phase that directly involves the supplier, an agreement is in place so that a fee of 70 € has to be corresponded for every defect generated by the supplier, and the man-hour loss bore by Tetra Pak has to be refunded as well by the supplier. A more collaborative aspect of suppliers relationship is represented by the agreement in place so that whenever an error is encountered that involves the supplier, the supplier with the collaboration of Tetra Pak technicians has to identify within 2 weeks from the problem detection the root cause of the problem (5 whys analysis, Ishikawa diagram or others).

5.3.4 Lean testing activity

Despite a product modularity was achieved before the implementation of WCM, the breakthrough for testing activities was constituted by the possibility of actually carrying out separate tests on individual modules. This has been made possible by the introduction of a simulator allowing modules to be tested at the suppliers' site and therefore originating the actual configuration of the testing process as depicted in Figure 22. As opposite, before the introduction of WCM, no distinction existed between external and internal testing, being both performed internally at Tetra Pak. The situation as it was could be depicted in Figure 23.

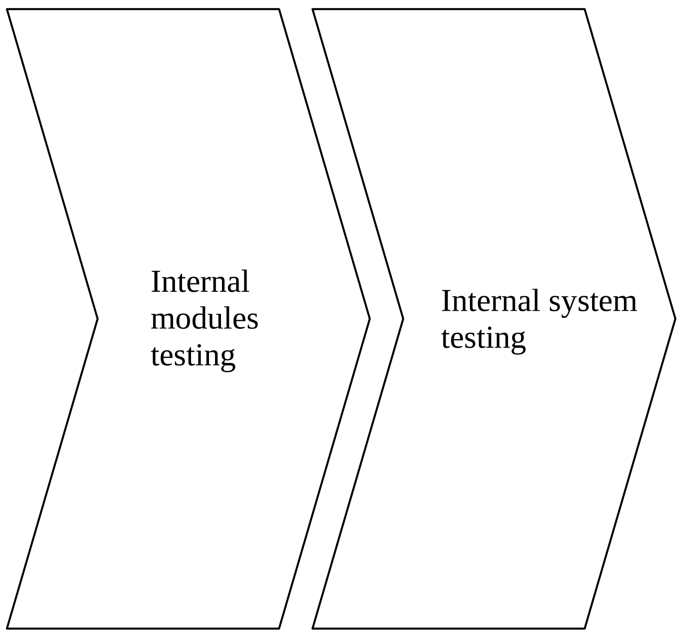

Figure 23 - Testing process at TetraPak before the World Class Manufacturing implementation

The two different approaches lead to significantly different performances. Considering Internal Lead Time as a KPI for testing process, we have:

- Internal Lead Time after WCM implementation: 20 working days.
- Internal Lead Time before WCM implementation: 30 working days (+50%).

With regards to current internal testing activities, the processes are highly structured. A good summary of the process can be given by analyzing the following elements:

- Process ownership. Each machine undergoing testing is assigned to a "machine owner" which is responsible for carrying out the testing procedures and ensuring the quality standards. Additional operators (generally two or three) assist the machine owner in the more manual phases of machine assembly and disassembly. The Quality and specialized personnel in Automation or Mechanics intervene in the process whenever an error during testing is encountered and cannot be solved by the machine owner.
- Process procedures. The testing process is highly structured. Each machine owner is responsible for carrying out a series of procedures as listed on a testing manual. This has been created by a pool of internal specialists over a year-time and includes twenty macro phases, which in turn refer to ten sections, namely:
    - Machine assembly
    - Electrical and mechanical wiring
    - Assembly kit UV lamps
    - Software download
    - ICU test (cleaning unit)
    - Speed test
    - Mechanical settings
    - Sealing checks
    - Pressures checks
    - Final test
    - Electrical and mechanical disassembly.

  These procedures are constantly under review in order to improve the task and possibly to reduce the time needed. The most relevant savings have been identified in the final test, which over years has been reduced from six hours to two hours. A critical factor that allows this saving is identified as the position of the machine along its product lifecycle; the production process for machines already commercialized for a few years is indeed more stable and therefore provides more reliable quality that the one for a newly released machine, thus determining the need for a less strict testing.
- Process control. The overall testing process is centrally monitored via Information System. Tetra Pak implements a proprietary software ("Production monitoring") that allows having

an overview of the up-to-date status of each machine undergoing testing. The inputs are provided by the machine owners which are equipped with a terminal for manual data entry in the system. Each machine owner would regularly enter certain type of information regarding the machine undergoing test that they are currently responsible for. This information refers to:

- Procedures currently completed.
- Problems identified during the execution of a specific procedure. The system handles this information by recalculating the progress time of testing for that specific machine, according to standard times. At the same time, a specific section is made available for the operator to record all the activities performed in order to solve the problem encountered.

This type of system allows three evident benefits:

- Up-to-date monitoring of machine tests status (the usage of a GUI makes this information intuitive by representing the current layout with machines undergoing testing, and a color code for each machine where green represents a machine whose testing is on-schedule, red represents a machine whose testing is delayed and yellow represents a machine whose testing might be delayed).
- Creation of a library for problem-solving practices. The systematic record of activities performed in order to solve problems encountered during the testing of a machine allows creating a repository of best practices.
- Activity planning for Quality and specialized personnel in Automation or Mechanics that has to intervene on machines which have encountered problems during testing that cannot be solved by machine owners.

5.3.5 Operators’ perspective

The shop floor working environment is organized in such a way to respect the WCM operative standards. Particularly, the following techniques have been regularly implemented since 2008:

- 5S (one audit each week).
- Kaizen teams (teams built with different competencies across departments, and allocated one week full time to a specific project).

- TQM (an example of outcome of this initiative is represented by the introduction of the "machine owner" role).
- Visual control (through the implementation of "Production monitoring").

The outcome of these initiatives from the test engineer standpoint are increased quality along the process and increased responsibilities for the operators themselves, this resulting in higher motivation and personal satisfaction.

5.3.6 Stocks

The only items managed with a stock within the testing workshop are consumption materials (paper rolls, operating equipment). Therefore no stock-keeping policy exists within this structure.

Extending this consideration to the supply chain, no stock is kept or physical supplies arranged in behalf of first tier suppliers (modules manufacturers). The only intervention in this sense is represented by the arrangement of framework agreements with particular categories of suppliers (for instance on the base of higher bargaining power). Nonetheless, the physical supplies also in this case are directly handled by the supplier itself.

5.4 Testing KPIs

Three main categories of KPI are monitored within the testing process, namely:

- Quality-related KPI
- Time-related KPI
- Cost-related KPI.

Quality-related KPI mostly refer to the number of defects identified during testing. The most relevant ones are:

KPI	Before WCM	After WCM (2009)

Number of errors identified during testing	N.A.	N.A.
Number of errors encountered during machine installation and start-up at customer's site	N.A.	N.A.

Time-related KPI mostly refer to Lead Time. The most relevant ones are:

KPI	Before WCM	After WCM (2009)
Internal Lead Time	30 working days	20 working days
Order-to-dispatch*	N.A.	122 working days
Order-to-performance**	Approx. 500 working days	259 working days

* time span elapsing from receipt of the order to the moment of dispatch of the final machine including queue + external lead time + internal lead time + stock.

** time elapsing from receipt of the order to the moment of dispatch of the final machine including queue + external lead time + internal lead time + stock + transportation + customs clearance + installation and start-up.

Despite data are not always available for the above mentioned KPIs, the scenario depicted by the interviewees clearly identifies a general improvement trend for the values of Time-related KPI and Quality-related ones after the adoption of WCM.

Section 6: Comparative analysis of the case studies

Abstract

A comparative analysis has been carried out on the three case studies analyzed (Company, Company2 and TetraPak) in order to identify common features and discrepancies within the three different testing processes, with the aim of identifying best practices that can be of use in a second stage in order to develop a general model for the optimization of a generic manufacturing testing process.

This section is composed of two main parts.

A series of variables considered as relevant for the description of a testing process are at first defined.

The comparative analysis of the three case studies is then performed on the base of the values that the descriptive variables identified assume in each of the three cases.

6.1 Descriptive variables

In order to perform a complete analysis, a series of variables that could be considered as relevant for the description of a certain testing process had to be defined.

The core elements to be included in process description have been identified as:

- Production and Product features
- Testing process
- Supply Chain.

Production features have been identified as significant pieces of information to take into account when describing the company's operative configuration. The variables taken into account are therefore:

- Volumes ("Production volumes")
- Variety ("Production variety")
- Way of responding to the demand ("Production management")

- Position of the scheduling point (“Scheduling Point”).

So that it is possible to assess the positioning of the company on the volume-variety matrix (Figure 24).

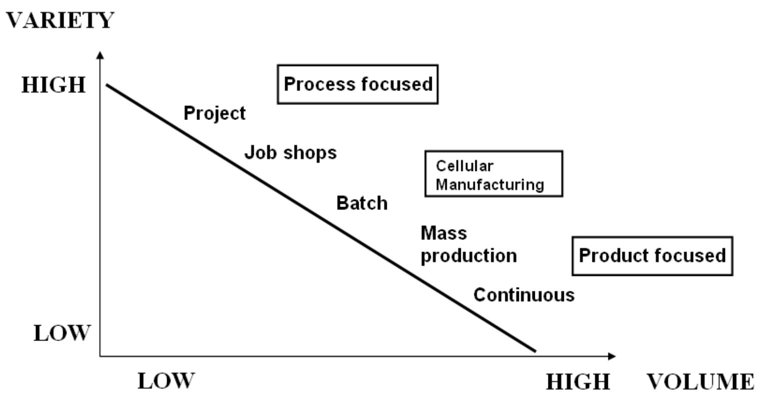

Figure 24 - Volume-Variety Matrix

Product features are examined from a testing standpoint, therefore taking into consideration the following variables:

- Product modularity (“Product composition hierarchy”).
- Number of suppliers per single product (“Product funneling”).

These variables are of significance from the testing standpoint since they determine the characteristics of the product which is fed into the actual testing process in relation to the immediate upstream stage (the supplier/s providing the product or product components as for the definition we gave of testing process in section 1.2).

The characteristics of the testing process according to the definition we agreed upon are then taken into account. The main variables to determine these characteristics have been identified as:

- Presence of collateral activities to testing within the testing process (for instance software development, engineering, etc.) (“Presence of collateral activities to testing”).
- Presence of setup activities within the testing process (“Test setup”).
- Presence of stocks in the system (“Stocks”).

These variables identify the central elements that characterize a Value Stream Map analysis, namely the identification of value, the activity blocks, the presence of inventories between the activity blocks.

Testing process also includes some variables related to the core testing process activity, or "testing activity":

- Scope of testing ("Scope of testing").
- Availability of procedures for testing ("Procedures").
- Tests outsourcing ("Outsourcing").
- Parallelization of testing activity ("Parallelization").
- Error-solving practices ("Errors resolution").

These variables aim at identifying possible tests modularity (for instance tests on modules and tests on the whole machine or system), tests externalization and tests parallelization with the objective of tests Lead Time reduction. Furthermore, they are aimed at assessing possible structured procedures already in place in both testing and error-solving activities.

Testing process also include some variables related to workforce management. These have been taken into account in the testing process description, being the allocation of available resources on the activities a parallel flow to activities management itself. The variables taken into consideration are:

- Dimensioning of both external and internal personnel capacity ("Personnel dimensioning").
- Degree of autonomy left to testing personnel ("Personnel empowerment").
- Personnel allocation planning methods ("Personnel planning").

Supply Chain needs to be included in our considerations as a fundamental integrative part of the testing process. Accordingly to the given definition of testing process, the product is fed into the testing process via an external supply chain, since no internal manufacturing activity is included in the process. It emerges from this point the necessity for the process description to be carried out by considering the characteristics of the Supply Chain in terms of:

- Number of customers served ("Number of customers").

- Type of relationship with the customers and bargaining power (“Relationship with customers”).
- Number of suppliers (“Number of suppliers”).
- Type of relationship with suppliers, whether collaborative or traditional (“Relationship with suppliers”).

A series of relevant variables for the description of a testing process have been defined.
The variables can be clustered in a few categories: Production features, Product features, Testing process, Testing activity, Supply Chain and Workforce management.

The three case studies presented so far are now going to be compared on the base of the identified variables.

6.2 Comparative analysis

Once defined the variables and their significance for an exhaustive description of a testing process, a comparative analysis among the three analyzed case studies can be carried out. In this section, Tetra Pak would be referred to as “TP”, Company as “C”, Company2 as “C2”.

6.2.1 Production and Product features

- Production volumes. Production volumes are considered high in TP (about 300 tested machines per year) and low in both C and C2 (with a number of tested systems in the order of magnitude of 10 per year for C).
- Production variety. Variety is considered low for TP (only three machine models tested) and high for both C and C2 (each system represents a unique project).

- Production management. TP operates according to a Make-To-Order logic, having implemented a takt time; while no concept of takt time is identified in both C and C2 which work on traditional Engineer-To-Order.
- Scheduling point. TP has a single scheduling point along its testing process, positioned in correspondence of the testing activity. C has a double scheduling point, one in correspondence of testing activity and one in correspondence of software development. This data is not available for C2.
- Product composition hierarchy. In all the three cases the concept of product module exists. In TP case the modularization for the product can be identified on a two-levels hierarchy composed by single modules at the bottom level and the assembled machine at the top level. In both C and C2 case the modularization can be identified on a three-levels hierarchy composed by single modules at the bottom level, typical-replica distinction at the intermediate level and the whole system at the top level.
- Product funneling. One single TP machine is composed by modules supplied by 6/7 different suppliers, while for C and C2 one single suppliers feeds the testing process with all the modules composing the whole system.

6.2.3 Testing process

- Presence of collateral activities to testing. The process in TP does not include any other collateral activity besides testing. On the opposite, both C and C2 present collateral activities, namely engineering and software development.
- Parallelization of collateral activities with testing activity. We have a partial parallelization of collateral activities in the C case, while no collateral activities exist in the TP case and no data is available for the C2 case.
- Test setup. In TP and C case, some setup activities are performed on the system or machine before it undergoes testing. In TP the setup activities can be considered as optimized since they underwent a systematic reorganization in a WCM perspective (5S, SMED). On the opposite, in the C case setup activities are carried out in a non-optimized way, with systematic inefficiencies as discussed in the main case study (section 3). C2 does not present setup activities since the testing is performed at a supplier’s site, and set up activities are not bore by the company itself.

- Stocks. No significant stocks are present in the system in TP case (besides negligible consumption materials and operating equipment). On the opposite, significant stocks are present in the system in C case as a result of the policy of managing supplies for the modules supplier and for software development internal activity.
- Scope of testing. In the three cases, tests can be modularized as "tests on individual module" and "tests on the whole system or machine".
- Outsourcing. The three cases present a very different situation in terms of outsourcing. TP externalizes around 50% of the total tests to be performed on the machine to modules manufacturers, which are in charge of performing a predefined set of tests on the individual module of their competence. C externalizes just electrical, mechanical, functional, capacity and continuity tests (about 20% of total tests.). C2 completely externalizes the testing procedures, which takes place at the supplier's site but employing personnel from C2.
- Parallelization. Also with respect of the "parallelization" variable the three cases present quite a different scenario. TP parallelize the module tests at the supplier's site to then perform the system integration test in-house. C parallelize the testing activities to a lower granularity level with respect to TP. In fact, C tests at the same time a typical modules and the correspondent replica ones. Finally, C2 does not parallelize the testing activities at all. C2 starts testing the replica modules only once the typical ones are already testing, therefore it does not exploit the testing parallelization benefits despite that they have both a modularized product and procedures.
- Procedures. TP implements highly standardized procedures for machine testing. C implements standardized procedures which are though not rigorously followed, since in most cases the customer asks for extra tests which are not included in the initial procedures. C2 follows the practice of agreeing with the customer upon semi-standardized procedures, which become standardized once the customer has signed for acceptance. This prevents the customer asking from extra tests which have not been initially agreed upon.
- Error-solving. Error solving procedures are handled in a very different way depending on the three cases. TP operates with a quite structured error solving procedure, implemented via the centralized software control tool and offering a database of error-solving actions tailored upon the type of error encountered during testing. C does not have error-solving procedures in place: the error-solving phase is delegated to the individual operators carrying out testing and it relies on verbal communication both for practices sharing and problem handout to people with a major or different expertise operating in testing process (for instance a systems engineer). Data regarding this feature are unavailable for C2.

- Personnel dimensioning. The capacity dimensioning of personnel working on testing activities is different in the three cases. TP works with internal personnel, acquiring extra capacity in order to chase demand peaks, if any. The regular capacity in C is built with internal and external personnel for both test and software development activities. C2 operates with internal personnel for both test and software development activities.
- Personnel empowerment. TP promotes personnel empowerment, according to the implemented TQM principles (for instance through the creation of a process owner). C personnel operates on the opposite in a more traditional environment, where little empowerment is promoted. C2 presents an intermediate situation where one can find a sort of "system owner" concept in the practice of allocating the same operator to both factory tests and on-the-field tests for the same system.
- Personnel planning. Capacity allocation takes place in TP in a centralized and structured fashion. Test engineers are allocated to incoming machines on the basis of a FIFO system depending on their availability. The allocation of Quality and Automation Personnel is carried out on the basis of up-to-date need as communicated via "Production Monitoring" tool. Capacity allocation in C takes place in a centralized fashion per activity type (software development or testing personnel), although unstructured and mostly relying on verbal communication.

6.2.5 Supply Chain

- Number of customers. TP serves multiple customers and so does C2. C on the opposite serves, as for the limitations considered in the case study, a single customer.
- Relationship with customers. TP maintains collaborative relationship with its customers. This is especially true for the most relevant ones, whose possible product customization requests are usually dealt with directly from the R&D department in the perspective of a mutual benefit. C maintains a collaborative relationship with its only customer. This also includes practices sometimes detrimental such as the availability of C to adapt to particular requests upon test procedures change made by the customer during the system test. C2 appears to have a more traditional relationship with its customer, based for instance on mutually agreed procedures that cannot be modified while tests are in progress.
- Number of suppliers. TP currently keeps a base of twenty suppliers, while C has one and C2 keeps multiple suppliers on the basis of a multiple sourcing strategy.

- Relationship with suppliers. TP maintains collaborative relationships with suppliers, as widely explained in the case (section 5). This includes leading the suppliers to adopt the company's takt and promoting initiatives of suppliers' growth at its own expenses. C maintains a traditional relationship with its supplier, with poor outcomes in terms of coordination and incoming quality, as explained in the case (section 3). D maintains traditional relationships with its customers, though possible criticalities emerging from this fact are not known.

Variable category	**Descriptive variable**	**Tetra Pak (TP)**	**Company (C)**	**Company2 (D)**
Production features	Production volumes	High	Low	Low
	Production variety	Low	High	High
	Production management	MTO	ETO	ETO
	Scheduling point	Test Activity	Test Activity and Software development	N.A.
	Product composition hierarchy	• Module • Machine	• Module • Typical/Replica • System	• Module • Typical/Replica • System
	Product funneling	6/7 suppliers per machine	1 supplier per system	1 supplier per system
Testing process	Presence of collateral activities to testing	N	Y	Y
	Parallelization of collateral activities with testing activity	-	Partial	N.A.
	Test setup	Y optimized	Y non optimized	N
	Stocks	N	Y for suppliers	N
	Scope of testing	Module + machine	Module + system	Module + system
	Outsourcing	50% total test	20% total test outsourced	100% total test outsourced

		outsourced		with internal personnel
	Parallelization	Y at a module level	Y at a subsystem level (typical/replica)	N
	Procedures	Structured	Semi structured	Structured and customized
	Errors solving	Structured	Unstructured	N.A.
Testing process	Personnel dimensioning	Internal + external on peaks	Internal + external	Internal
	Personnel empowerment	Y	N	Y
	Personnel scheduling	Centralized and structured	Centralized per activity type and unstructured	N.A.
	Personnel dimensioning	Internal + external on peaks	Internal + external	Internal
Supply Chain	Number of customers	Many	1	Many
	Relationship with customers	Collaborative	Collaborative	Traditional
	Number of suppliers	Many	1	Many
	Relationship with suppliers	Collaborative	Traditional	Traditional

Table 1 - Comparison of the three case studies

6.3 Conclusion

Within this section, the relevant descriptive variables for a manufacturing testing process have been identified.

The three case studies analyzed in the previous sections (section 3, 4 and5) have been compared on the base of the previously defined descriptive variables.

The comparison of the three case studies has highlighted both similarities and discrepancies with respect to the different categories as it can be appreciated in Table 1.

The findings deriving from the cases comparison will be further developed in the next section with the aim of generalizing them beyond the three specific cases analyzed.

Section 7: Framework development

Abstract

This section is dedicated to the generalization of the results emerged from the analysis of the three case studies and their comparison. The outcome of this generalization is a framework aimed at assessing the features of a specific test process according to some variables that have been identified as significant for the process description.

The section is structured in two main sections.

At first, the variables identified as of significance for the description of a test process are introduced. Also, a set of key performance indicators for a generic testing process are identified.

Each variable is then punctually analyzed. An assessment method is proposed for the attribution of a value to the specific variable. A set of guidelines is then proposed on the base of the possible values the variable can be attributed. Last, a qualitative evaluation of the impact of the proposed guidelines on the key performance indicators for a testing process is proposed.

7.1 Descriptive variables and key performance indicators for testing

On the base of the literature analysis (section 2), the comparative analysis of the case studies (section 6) and the identification of a set of best practices within the case studies (section 6), it is possible to proceed with a broader generalization of these considerations for a generic testing process as we defined it.

The outcome of this generalization is a framework. This framework is aimed at assessing the characteristics of a generic testing process according to a set of significant variables. On the base of the identified characteristics, the framework also aims at proposing a series of guidelines oriented towards process optimization, either in terms of Lead Time reductions, or Cost reductions, or Quality improvements.

The logical structure of the framework is presented in Figure 25.

Immediately following, we present a detailed explanation of the guidelines proposed on the base of the individual variables. The final framework, comprehensive of all the variables and a synthetic explanation of the guidelines is presented in Table 3.

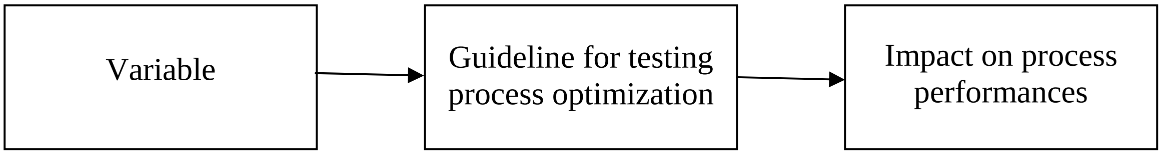

Figure 25 - Logical structure of the framework

Two descriptive variables have been identified on the base of the categories used to perform the comparative analysis among the case studies (section 6).

- Testing process.
- Testing Supply Chain.

In order to reduce the number of variables to be taken into account to the most significant ones, some variables presented in the comparative analysis have not been further considered, and those variables presented within the category Product and Production features that have been deemed of relevance have now been included in Testing process or Testing Supply Chain.

Each category includes multiple variables, namely:

- Testing process
  - Product modularization. This variable aims to assess whether the physical end product/system is already modularized.
  - Independent test modules. This variable aims to assess whether the testing process is already organized according to a module testing structure. We intend as 'test module' a specific subset of parts within the final product/system whose interconnected functioning is assessed by specific tests that do not involve other parts of the same product/system but the ones defined as 'test module'.
  - Test procedures structure. This variable aims to assess whether the testing activity is structured and standardized across the organization.
  - Out-of-process activities. This variable aims to assess whether the management of errors encountered during testing is managed in a structured rather than unstructured fashion.

- Personnel responsibilities. This variable aims at assessing whether the testing personnel is attributed responsibilities regarding the quality outputs of the final product/system.
- Testing setup. This variable aims at assessing the degree of standardization of setup activities performed on the product/system undergoing testing.
- Personnel scheduling. This variable aims at assessing the type of system in place for resources allocation and scheduling on the different products/systems undergoing testing.
- Collateral testing activities. This variable aims at assessing the presence of activities within the process that are collateral to the testing activity itself.

- Testing Supply Chain
  - Relationship with suppliers. This variable aims at assessing the type of relation in place with different suppliers, according to a chosen classification scheme.
  - Number of suppliers per product. This variable is aimed at assessing whether a single or multiple suppliers are involved in the first tier of the product/system supply chain.
  - Number and relevance of customers. This variable is aimed at assessing the number and relative relevance of customers served by the company under analysis.
  - Stocks. This variable aims at assessing the presence of stocks along the testing process.

With regards to the impact of proposed guidelines, a set of KPI has been defined for the testing process:

- **Total Lead Time**. Total Lead Time is intended as the total time elapsing between the start and the end of a testing process for a single product or system.
- **Internal Lead Time**. Internal Lead time is intended for a single product or system as the time elapsing between the start and the end of those activities, part of the testing process, that are carried out within the boundaries of the testing company. This performance measure is of particular interest whenever decisions of externalizing part of the testing process or of the testing activity itself can be taken. This gives rise to a distinction between a Total Lead Time and an Internal Lead time.

- **Cost of Testing**. On the basis of the formulation proposed by Johnson, we identify two main components of Cost of Testing:
    - Fixed costs. We consider as part of this component the capital cost of test equipment, the engineering required for specific test system, and in general the cost of those initiatives undertaken with the specific purpose of improving the performances of the test process.
    - Recurring costs. We consider as part of this component all the variable costs incurred during testing, such as the cost of personnel, or consumable items, or others.
- **Quality**. Quality is intended on two levels:
    - At a first level, it is intended as outbound quality; it is representative of the overall defectiveness of products/systems outbound from the test process, and therefore it represents an overall measure of testing process effectiveness.
    - At a second level, Quality is intended as incoming quality; it is representative of the defectiveness of products/systems undergoing the test process, which introduces variability within the testing process through the occurrence of errors that have to be detected and solved.
- **Overall Testing Process Efficiency**. This performance indicator is intended as a general measure of the ratio between inputs and outputs of the testing process.

A series of relevant variables for the description of a testing process have been defined by further generalization from the ones used for the comparative analysis of the three case studies.
The variables can be clustered in two categories: Testing process and Testing supply Chain.

A set of significant KPIs for the testing process have also been defined: Total Lead Time, Internal Lead Time, Cost of Testing, Quality and Overall Testing Process Efficiency.
We are now going to present a punctual analysis on each of the descriptive variable. This includes

- A proposal of assessment method for each variable within a specific testing process.
- A proposed intervention in order to improve the performances of the testing process depending on the value assumed by the specific variable.
- An evaluation of the impact of the proposed interventions over the defined KPIs.

7.2 Product modularization

Assessment method

With reference to the literature analysis, a module can be defined as "a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units" (Baldwin & Clark, 2000). A module can also be thought as a "self-contained sub assembly that connects to other modules using common interfaces" (Arnheiter & Harren, 2006). Also, with reference to product architecture, a modular architecture can be identified when there is "one-to-one mapping between physical components and functional elements, and the interfaces between components are decoupled" (Ulrich, 1995).

We therefore propose that product modularization is identified when it is possible to acknowledge that:

- The product/system is exaustively composed by a set of units whose structural elements are powerfully connected among themselves.
- The structural elements composing each unit are relatively weakly connected to elements in other units, through common interfaces.
- There is one-to-one mapping between physical components and functional elements to be tested.

Guidelines

Product modularization represents a fundamental precondition for the partitioning of test into independent or semi-dependent subsets. The presence of independent modules indeed heavily influence the possibility of tests to be carried out on physically separated elements, with the sequence of possible implications explored in the next assessment dedicated to "independent test modules".

The proposed guidelines are tailored on the outcome of the assessment of product modularization, as follows:

- If :
    - no physical modularization is already in place.
    - or there is no correspondence between physical modules and functional elements to be tested.

then technical department should be involved in order to consider product reengineering. If massive product reengineering is required, a cost/benefit analysis should be performed.

The involvement of technical department in this sense could be regarded as a Design for Testing (DFT) approach. DFx techniques, in general, consist in a set of methodologies offered as a support to engineers in order to "better assess the downstream lifecycle impacts of their design choices" (Herrmann, et al., 2004). "x" represents any one of a variety of design considerations occurring during the product lifecycle; Inspectability, System Quality and Testing are among those. Design for System Quality addresses the need of complex products that are composed of different modules (sometimes a blend of software, hardware and external structures). In this case the key objective is achieving high reliability of the entire system, with primary attention to the interfaces among different modules, which can be subject to specific failure modes (Herrmann, et al., 2004). Design for Testability (DFT) itself can be defined as "a class of methodologies which put constraints on the design process to make test generation and diagnosis easier" (Wu, 2002). The technicalities of these approaches are out of scope for what it concerns this Thesis Work; it is nonetheless important to mention how these methodologies could be beneficial from the point of view of a re-engineering aimed at including testing requirements since the very beginning of the process.

- If the product is already modularized, and there is correspondence with the test modules identified, it should be pursued the delegation of tests on individual modules to the module manufacturer.

This would allow:

  - Externalization of individual modules tests and
  - Parallelization of the externalized modules tests, under the conditions expressed by the assessment on 'number of suppliers per product'.

It has to be noted how the possibility and the modality of externalization are determined in the following assessment "independent test modules".

The possibility of externalization depends also, to a lesser extent, on the outcome of the assessment 'relationship with suppliers'.

Impact on process performance

The proposed guidelines are aimed at achieving reductions in both Internal Lead Time and Total Lead Time. Particularly:

- Reductions in Total Lead Time are achieved through the parallelization of tests on individual modules.
- Reductions in Internal Lead Time are achieved on top of reductions on Total Lead Time, due to the externalization of test activities on single modules to module suppliers.

The guideline proposed in case physical modularization is not in place or there is no correspondence between physical modularization or test modules can have a negative impact on the Fixed Costs if product re-engineering has to be undertaken.

7.3 Independent test modules

Assessment method

We define test modules as specific parts of the product/system whose interconnected functioning is assessed by tests that do not involve other parts of the product/system but the ones defined as a test module.

We consider a distinction between independent and interdependent test modules, as follows:

- Independent test modules. These types of modules respect "in toto" the definition of test module provided: each module represent the object of a test set that does not require the interaction with other modules.
- Interdependent test modules. These types of modules partially respect the definition of test module provided: each module represent the object of a test set that can be divided in two subsets, one that does not require the interaction with other modules and another one that does (in this case it is possible to refer to the two tests subsets as 'standalone tests' and 'system -or integration- tests').

A third case can be possible, where no modules can be identified. In this case, the structure of tests procedures, given as a constraint, does not allow the identification of tests modules; it is possible to match this case with the existence of the sole subset of 'system -or integration- tests' with no 'standalone -or unit- tests'.

Guidelines

The proposed guidelines are based on the distinction between unit and integration test. Unit tests are those tests performed on a defined unit of the product/system, while integration tests are performed on the interface between two units that have already been tested. Integration tests are specifically aimed at identifying problem that occur when units are combined, given that the quality of individual units themselves has previously been ensured through unit tests (Visual Studio, 2010).

Furthermore, the proposed guidelines are tailored on the extent to which test modules can be identified:

1. If the product/system is, or can be, composed by independent test modules, tests can be carried out 100% as standalone tests on test modules.
2. If the product is, or can be, composed by interdependent test modules and there is possibility to develop a simulator to simulate the interface with other test modules, tests can be split in two parts:
    - tests on individual modules that can be parallelized using a simulator to simulate the interface with other test modules.
    - 'system tests' on the whole system.
3. If the product is, or can be, composed by interdependent test modules, tests can be split in two parts:
    - tests on individual modules that can be parallelized.
    - 'system tests' on the whole system.

   It has to be noted that in this case the proportion of tests that can be carried out on individual test modules are a lower proportion than in case 2. due to the absence of a simulator that partially overcomes the problem of modules interdependence.
4. If no test modules can be identified, then the technical department should be involved. If massive test reengineering is required, a cost/benefit analysis should be performed.

Given the condition of independent test modules as the ideal one, it is necessary to highlight how the driver behind each of the guidelines proposed is the achievement of a situation where the independency of test modules is leveraged to a maximum extent given the current product/system constraints.

Moreover, whenever the trade off cost/benefit makes it convenient, the R&D should be involved with the purpose of product or test redesign in all the cases 2., 3. and 4.

Figure 22 summarizes the four guidelines exposed above.

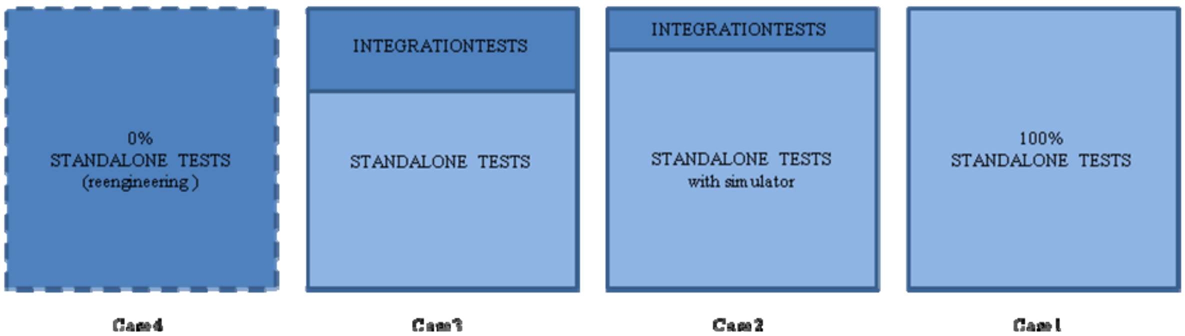

Figure 26 - Guidlines for indipendent test modules

The guidelines proposed with assessments ‘Independent test modules’ and ‘Product modularization on the base of test modules’ and their interaction can be further clarified. The proposed guidelines are aimed at having a combined effect on the allocation of testing activities over time and space. We can identify four conceptual stages (Figure 27):

1. No test module is identified; therefore all the testing activity is carried out as systems test.
2. The test activity is separated into standalone tests and system tests; therefore, despite no physical modules are identified, it is possible to perform a portion of the total tests on individual parts independently from the total system.
3. A physical modularization is identified, overlapping with the identified test modules. Product modularization represents the precondition for standalone tests to be carried out in a physically separate fashion, and possibly externalized to different locations.
4. The product/system modularization is fully enhanced by the delegation of standalone tests to module suppliers. The effect over the reduction of Internal Lead Time is evident.

The relative preponderance of the system tests part on the standalone tests one depends on the degree of tests independence achieved, as exposed in Figure 22.

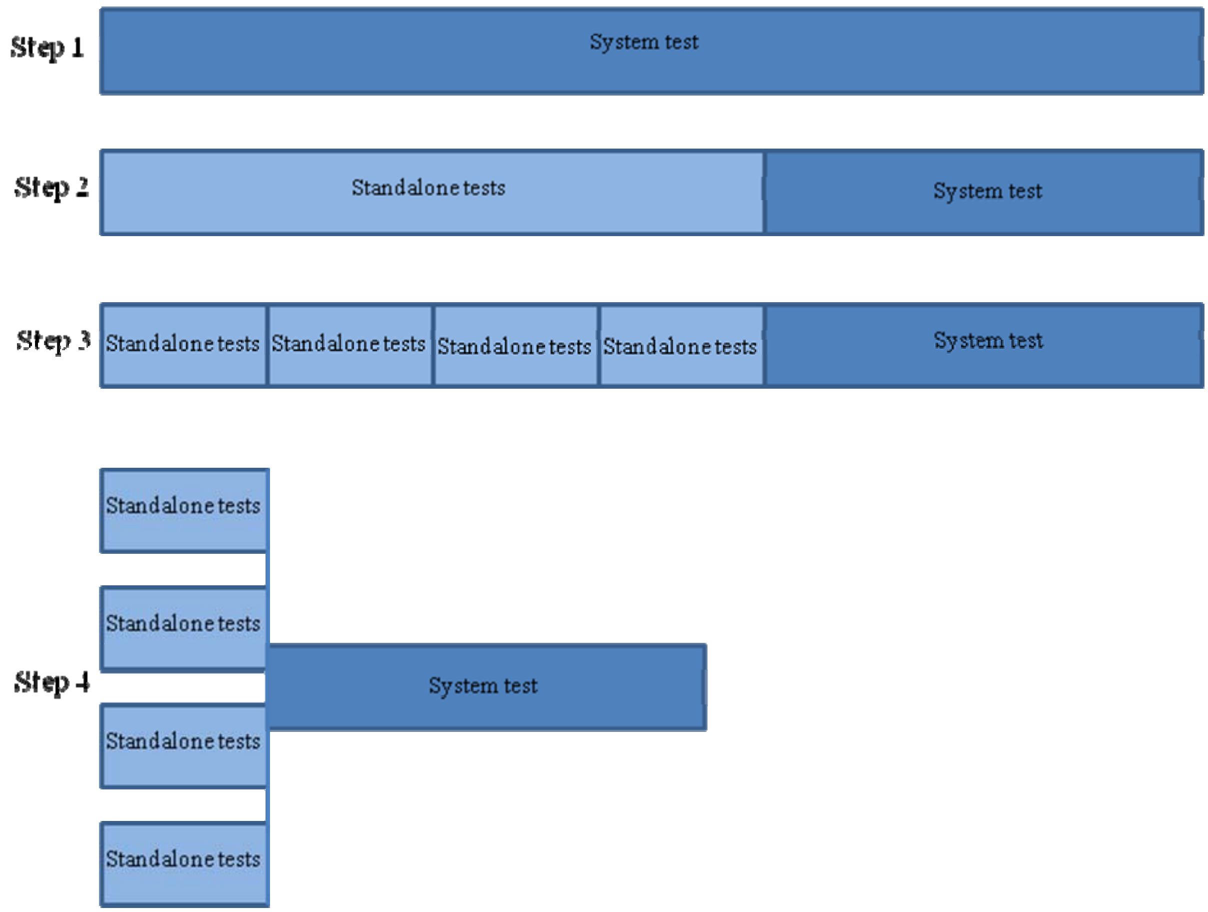

Figure 27 - Guideline for product modularization on the base of test modules

For the sake of clarity, we can propose an example for each of the four steps identified. Let's consider for instance an electrical gearmotor (a motor combined with a reducer) whose characteristics that need to be tested are the electrical isolation, the electrical absorption, the number of spins per minute and the level of noise at normal working conditions.

In the first case, we consider this gearmotor to be assembled on the same platform component by component. Once the assembly operation is completed, the motor undergoes test. Therefore, all the tests are carried out as system tests (Step 1).

In the second case, the gearmotor is also assembled on the same platform component by component. In this case, though, the electrical isolation test is performed on the stator as soon as it is assembled on the platform. All the remaining components are then assembled and the other tests are performed. In this case, one test is carried out as standalone test and all the others as system tests (Step 2).

In the third case, the product is explicitly conceived as composed by two modules, a motor and a reducer. These are assembled and tested separately. As a final step, the two modules are coupled and a final integration test is performed. In this case, standalone tests are carried out on physical product modules, and a final system test is carried out on the final assembled product (Step 3).

In the fourth case, the motor is assembled and tested by one company, and the reducer is assembled and tested by another company. The company under analysis then performs the final coupling of the two modules and the final system test. In this case, the standalone tests are carried out concurrently on physical modules externalized to suppliers, while the final integration test is performed in-house on the fully assembled product (Step 4).

Impact on process performance

As for the performed literature analysis, the possibility of modularizing testing activities brings along significant opportunities in terms of Lead Time reductions and overall process optimization.

The guideline proposed promotes the maximum level of modularization achievable on current testing activity, compatibly with existing constraints. Benefits arising from test modularization can be identified in:

- Shorter Total Lead Time, when test modularization is combined with the possibility to parallelize multiple test modules. (Onoma, Tsai, Poonawala, & Suganuma, 1998).
- Increased inbound and outbound Quality, when test modularization is combined with the possibility to parallelize multiple test modules. In this case the anticipation of test modules allows early identification of errors and the prevention of their propagation along the testing chain (Ntafos, 1998). Even when parallelization of multiple test modules does not take place, a positive impact on quality can be given by modularity itself, if that implies an enhanced ease in tracking errors within the single module and its possible replication in the others; this emerged for instance in one of the case studies analyzed.
- Reduced Recurring Costs, when test modularization is combined with the opportunity to parallelize multiple test modules, due to the possibility of anticipating module testing through parallelization. This helps preventing the exponential increase in cost of failure the later they are detected along the testing chain (Ntafos, 1998).

As mentioned in the points above, benefits arise from the possibility of concurrently carrying out tests on individual product modules.

7.4 Relationship with suppliers

Assessment method

The degree of collaboration that characterizes a customer/supplier relationship can be defined on the base of a set of elements, among which we find mutual commitments of assets, information exchange and degree of separation of technological and functional systems (Sheu, Yen, & Chae, 2006). According to this definition, we propose that

- A customer/supplier relationship is considered as traditional when it is characterized by non specific asset investments, minimal information exchange, and separable technological and functional systems within each firm.
- A customer/supplier relationship is considered as collaborative when it is characterized by specific asset investments, significant information exchange, and integrated technological and functional systems across the firms.

Guidelines

The guidelines proposed are tailored on the type of relationship identified for each supplier:

- For all those suppliers that classify for collaborative relationships it is suggested to:
    - Set framework agreements with suppliers in order to secure supplies.
    - Extend the takt to suppliers, whenever a takt can be defined.
    - Delegate the modules tests to suppliers, whenever individual tests can be performed on modules.

  Incoming quality in this case is ensured by the certification of positive outcome for those tests performed in-house by the supplier. Concerning all those parts whose functionalities are not tested by the supplier, contractually agreed-upon penalties for unsatisfactory quality and quality audits should be introduced.

- Whenever a supplier is identified as 'traditional', the approach must be oriented to maintaining quality of supplies through:
    - Introduction of contractually agreed-upon penalties for unsatisfactory quality and introduction of quality audits.

Impact on process performance

- The identified guidelines have a positive impact on incoming Quality, due to the central attention on those measures aimed at ensuring the level of incoming quality (audits and contractual penalties).
- Moreover, the extension of takt time and the delegation of modules tests in all the cases of collaborative relationships contribute to the improvement of performance in Total Lead Time and Internal Lead Time. The extension of takt time to the first tier suppliers allows indeed the pull flow to be extended, while the delegation of modules tests allows tests parallelization and externalization, as already mentioned in the 'test modules' section.
- The guidelines might have a negative impact on Fixed Costs whenever dedicated investments have to be undertaken in order to develop a collaborative relationship.

7.5 Number of suppliers per product

Assessment method

The number of suppliers per product/system is assessed as the number of different first-tier suppliers for a single unit of the product/system under consideration.

Guidelines

The proposed guidelines are tailored depending on the presence of a single or multiple first-tier suppliers per product:

- In case of multiple suppliers per product/system unit, it is recommended to coordinate the flow of inbound materials. This can be for instance implemented with a centralized milk-run picking from suppliers (whenever distances among different suppliers allow so) in order to coordinate the shipments with the required date for testing process to begin. This brings along the elimination of intermediate stocks as well.

Impact on process performance

- The synchronization of shipments has a positive impact on the overall testing process efficiency, due to the elimination of stocks in the system, and the elimination of multiple handling activities on product/system components that would derive from an unsynchronized material shipment.
- The need for multiple resources in parallel in the case of single supplier would possibly decrease the resource saturation, therefore negatively affecting Cost of testing. This kind of drawback is potentially offset by the benefit deriving from the reduction in Total Lead Time due to parallelization of tests; this trade off needs to be taken into account.

7.6 Relevance of customers

Assessment method

A Pareto analysis is proposed as a method for the assessment of customer relevance. It is important to notice that this assessment is not aimed at attributing the variable a single value, but in discriminating the served customers into two not overlapping and exhaustive categories.

- We define as highly relevant the 20% of customers that generate 80% of revenues (80/20 Customers).
- We define as lowly relevant the 80% of customers that generate 20% of revenues (20/80 Customers).

Guidelines

The proposed guidelines are tailored depending on the classification of considered customers as ‘80/20’ or ‘20/80’. In both cases the guidelines are aimed at limiting customer interferences in the testing process. Due to the criticality of testing activities, customer interferences often arise on the base of the customer’s will to have more or different product/system functionalities tested, so to have a better guarantee of the outbound quality. The proposed guidelines are:

- With the 80/20 customers, a collaborative strategy for testing procedure definitions should be adopted. It is important to reach agreements so that once the procedures have been mutually agreed, no extra-tests can be asked by the customer during the testing phase.

- With the 20/80 customers, a predefined set of standard testing procedures should be proposed. It is important to highlight how the Pareto classification represents a rule-of-thumb discriminator for identifying the most strategically important customers.

Impact on process performance

- The proposed guidelines positively impact the Total Lead Time, reducing its variations due to customer interference. This usually impacts on the Total Lead Time as extra time needed for performing additional tests.
- The proposed guidelines positively impact the Overall testing process efficiency, embanking those disruptions in the process (re-scheduling of activities, personnel reallocation, delays) that derive from customer interferences in the testing process.

7.7 Test procedures structure

Assessment method.

Test procedures can be considered as structured when codified in a “fixed, step-by-step sequence of activities or course of action (with definite start and end points) that must be followed in the same order” (Procedure definition, 2010) in order for testing to be considered correctly performed.

Guidelines.

Whenever not already in place, codified written procedures should be set up for both

- Test activities.
- management of out-of-process activities (those activities performed whenever an error is encountered during regular test activities), as discussed in the dedicated point ‘out-of-process activities’.
- out-of-process activities themselves, when these can be considered as ‘structured’ according to the correspondent assessment in the dedicated point ‘out-of-process activities’.

It is important to highlight the difference between procedures for testing/out-of-process activities and procedures for the management of out-of-process activities. In the first case, it is the test activity itself/the out-of-process activity itself to be standardized with a procedure. In the second case, it is the management of out-of-process activity to be standardized with a procedure, and not the out-of-process activity itself. This case takes place whenever the actions to be undertaken to solve a certain error occurring can be many and unstructured, while the steps for managing the occurrence of an error can be framed in a procedure (one can think of the Tetra Pak case, where as soon as an error occurs, the machine owner has to follow a procedure that includes reporting the error in the production management system, and keeping record of all the unstructured actions undertaken to solve the error; in this case the error-solving action is not framed by a procedure, but the error-solving management is).

Impact on process performance

The proposed guideline positively impacts:

- The Total Lead Time; activity standardization and implementation of procedures are indeed widely acknowledged tools for reduction of processing times (Jayaram, Vickery, & Droge, 1999).
- The outbound quality; stardardized work instructions are generally acknowledged having a positive impact on the quality result (Rooney & Rooney, 2005) (Hutzinger, 2006); in this case instructions would positively impact quality since they ensure that testing operations, aimed at errors detection, are properly carried out.
- The overall testing efficiency; the implementation of procedures and work standards have a positive impact in the reduction of process variability (Arnheiter & Maleyeff, 2005) (Hutzinger, 2006).

The proposed guideline negatively impacts:

- The Fixed Costs, due to the cost of creating procedures.

7.8 Out-of-process activities

Assessment method

Being testing a quality assurance activity, its output can be either positive (that meaning that the product/system undergoing a test fulfills the specific functional requirements that the test aimed to assess) or negative (that meaning that the same product/system does not fulfill the same requirements).

We define as "out-of-process activities" the set of actions undertaken whenever a negative result is given by a test. These can be of two types:

- Structured. We can consider out-of-process activities as 'structured' if they have a similar pattern independently from the type of error encountered, or have a similar pattern for clusters of errors encountered.
- Unstructured. We can consider as 'unstructured' those out-of-process activities where no significant pattern can be identified, either for different errors or different clusters of errors.

Guidelines

- If out-of-process activities are structured, codification through procedures should be achieved, as already covered by the 'test procedures structure' assessment.

- If out-of-process activities are unstructured, their codification cannot be achieved, as already discussed in the 'test procedures structure' assessment.

In this case, the guideline proposed follows a second assessment, based on two variables:

  - Order of magnitude of number of causes that can be possibly determining each type of error encountered during testing.
  - Number of different people that are possibly involved in the resolution of each type of error.

The proposed guidelines are:

- A high number of possible causes behind each error determines the need for a centralized information sharing on error-solving practices, implemented for instance through a library of best practices.
- A high number of people possibly involved in the resolution of errors determine the need for an integrated progress-monitoring system that allows specialist personnel to plan specific interventions when needed.

The definition of 'high' and 'low' levels for both variables is highly dependent on the context and a generic definition would be of scarce value. As a rule of thumb, it can be considered as 'high' a number of causes/different people that bring along a situation where the organizational costs of operating in the current state would outweigh the costs of implementing a centralized library of best practices or an integrated progress-monitoring system.

Impact on process performance

The proposed guidelines positively impact

- The Total Lead Time, as do the guidelines proposed for the creation of test procedures. Particularly, the creation of a library of best practices contributes to the reduction of "test downtime" that occurs when an error is encountered during testing.
- The overall Testing process efficiency. The benefit in this case is twofold. On one side the creation of a library of best practices avoids the duplication of activities that is incurred whenever a solution that has been previously implemented is not made available for future occurrence. On the other side, an integrated process-monitoring system allows a more efficient allocation of workload for personnel that have to intervene on faults.

The proposed guidelines negatively impact

- The Fixed Costs, due to the investments that would be required in order to implement both a shared library of best practices and an integrated process-monitoring system.

7.9 Personnel responsibilities

Assessment method

Job enrichment refers to the "process upgrading of an individual's responsibility" (Powell, 2002). We propose an assessment of employee empowerment based on the key features identified by (Caudron, 1995):

- Self-directed work teams.
- Free flow of information about company goals and directions.
- Training and continual development of work, management, and leadership skills by all employees.
- Managers who act like coaches and who empower gradually.
- Employee control of needed resources.
- Continuous positive feedback and reinforcement on performance.

Guidelines

Whenever not already in place, a system of responsibilities attribution should be implemented. This includes (Caudron, 1995):

- Activities such as "multi-skilling, cross training, self-directed work teams, and horizontal design".
- Human resource systems such as "learning and development, job enrichment/enlargement, peer review, and innovative compensation plans".
- Total quality management that involves line employees such as "statistical process control techniques, just-in-time inventory and delivery, and formalized supplier/vendor partnerships".

Impact on process performance

- The proposed guideline positively impact the outbound Quality (MacDuffie, 1995).
- The proposed guideline negatively impacts the Fixed Costs, due to the cost of initial personnel training, and the time dedicated to Total Quality Initiatives on a regular basis.

7.10 Stocks

Assessment method

The presence of stocks is identified as the existence in the system of materials in stocking, transit or buffer areas. Consumption materials, finished product, components, and subassembly or modules stocks have to be taken into account.

Guidelines

Being stocks a downstream consequence of the seven production wastes (Rother & Shook, 2003), their systematic elimination should be pursued.

- Concerning the product/system or its modules (whenever existing), the elimination of stocks can be achieved through a synchronization of shipments with the actual start of the testing process. In case of multiple suppliers for a single product/system, this can be achieved through a centralized and synchronized pick-up of modules in order to coordinate the shipments with the required date for testing process to begin, as already mentioned in the assessment 'number of suppliers per product'.
- Concerning components, an important consideration should be made on the control over components supplies for the first tier suppliers. If the testing company has bargaining power enough to guarantee convenient supplying deals to its first tier suppliers, the intervention should be limited to the intermediation for the supplier through a framework agreement and not to the direct managing of supplies. This brings along the elimination of components stocks managed in behalf of the first tier suppliers.

Impact on process performance

- The proposed guideline has a positive impact in the reduction of the Recurring Costs, due to the elimination of stocks in the system.
- Whenever components stocks managed in behalf of the suppliers are eliminated, a positive impact on the overall Testing process efficiency is achieved. This is due to the elimination of the extra degree of complexity brought by the management of first tier suppliers' components supplies.

7.11 Testing Setup

Assessment method

We intend as Testing Setup the set of preparatory activities performed on the inbound product/system or its modules in order for it to be ready for testing activity to begin. Testing Setup activities can include positioning, wiring, connection to testing devices and analogous operations.

Guidelines

Setup activities are traditionally regarded as non-value added activities. In this context, test setup activities represent non-value added time elapsing between the inbound receipt of the product/system or its modules and the beginning of the testing activity. Therefore, whenever not optimized yet, setup activities should undergo a reduction initiative. The proposed tools are the traditional Lean tools for waste elimination and setup reduction such as 5S and SMED.

5S is proposed being it of the “fundamental lean concepts, as it establishes the operational stability required for making and sustaining continuous improvement” (Chapman, 2005). The major benefits of implementing 5S have been identified in fast retrieval of items, improved staff involvement waste reduction, safer storage of materials, shorter lead times and better space utilization (Chapman, 2005) (Warwood & Knowles, 2004).

A 5S implementation includes five steps:

1. Sort. This first step requires employees to put aside whatever is acknowledged as not needed in the work environment; this can include parts, scraps, WIP, documents, packaging material, tools, machinery and operating equipment.
2. Set in order. What is kept in the shop-floor from the previous phase is made object of a careful organization within the available space in order to minimize operators’ wasted motion and material handling.
3. Shine. This step focuses on cleanliness; employees target areas to clean and determine the standards of cleanliness. The concept of “cleaning” in this phase also includes determining a check-up of equipment in order to identify early signs of wear-out.
4. Standardize. Specific stations should be set, containing appropriate supplies in order to maintain cleanliness within the working environment (brooms, mops, tags, etc.). Then, cleaning operations should be made part of daily activities.

5. Sustain. This last step is focused on helping the 5S develop its roots inside the company. This is more likely to happen when a multi-level involvement in the initiative is established across the company.

On the other side, the methodologies oriented towards setup reductions are mostly known under the name of SMED techniques. According to Shingo's first formulation of the techniques, the objective of SMED is readjusting setup activities so to minimize the number of setup operations that need to be performed during machine downtime, along with their duration. SMED approach to set-up reduction is fundamentally based on four conceptual stages, namely (Shingo, 1985):

- SMED step1: ensuring that external setup activities are carried out while the machine is still running.
- SMED step2: separation of external and internal setup activities.
- SMED step3: conversion of internal setup activities into external setup activities.
- SMED step4: improvement of all setup actions.

Impact on process performance

The proposed guideline has a positive impact on

- The reduction of Internal Lead Time, due to the compression of the time window elapsing between the product/system ready for testing and the actual start of the testing activity.
- The reduction of Recurring Costs due to setup.

The proposed guideline has a negative impact on the Fixed Costs due to the necessary investments for the development and sustaining of the Initiative.

7.12 Collateral testing activities

Assessment method

We intend as 'collateral activity' any primary activity performed within the boundaries of the testing company which can be directly related to the manufacturing of the product/system undergoing testing. It can be either a predecessor or a follower of the testing activity itself. An example of collateral activity is given by software development in Company case (section 3), or engineering and software development in Company2 case (section 4).

Guidelines

The general guideline for collateral activities is achieving their link in the process with the core testing activity through a continuous pull flow. In order to achieve this, it is necessary to verify the constraints on (Rother & Shook, Future state map, 2003):

- Activities cycle times.
- Resources dedication to single or multiple product families.

In order to achieve a final pull-flow configuration, we refer to the analysis proposed by Rother & Shook (Future state map, 2003), which is not further analyzed in this section due to scope limitations.

Impact on process performance

The proposed guideline has a positive impact in the reduction of Internal Lead Time, due to the achievement of a pull-sequencing across collateral activities and core central activity (Rother & Shook, Future state map, 2003).

7.13 Personnel scheduling

Assessment method

'Personnel scheduling' refers to the allocation of resources on the different activities within the process or to the different products/systems to be processed. Also, it refers to the scheduling of the different activities included in the process over a determined time frame.

We distinguish between:

- Centralized personnel scheduling. Scheduling activities are carried out at a centralized level for all types of resources and all types of activities.

- Decentralized personnel scheduling. Scheduling activities are carried out at a local level either for type of resource or for type of activity or both.

Guidelines

Whenever not implemented yet, personnel scheduling for both testing and collateral activities should be centralized so to guarantee visibility and efficiency in the allocation of resources.

Impact on process performance

The proposed guideline has a positive impact on the overall Testing process efficiency, due to the identification of a sole pacemaker process that "sets the pace for all the upstream processes" (Womack & Jones, 1996).

The proposed guideline has a negative impact on the Fixed Costs whenever its implementation requires dedicated investments.

Table 2 synthesizes the descriptive variables with the possible outcomes of their assessment. The combined effects of different variables are also indicated.

DESCRIPTIVE VARIABLE	**VALUE**	**COMBINED EFFECTS WITH**
1) Degree of product modularization	HIGH/ LOW	2), 3)
2) Degree of identification of independent functional modules	HIGH/ M-H/ M-L/ LOW	1)
3) Degree of strategic suppliers' relevance	HIGH/ LOW	1), 11)
4) Degree of procedure structuring	HIGH/ LOW	5)
5) Degree of out-of-process activities structuring	HIGH/ LOW	4)

6) Degree of personnel responsibility	HIGH/ LOW	-
7) Presence of stocks in the testing process	NO/YES	11)
8) Presence of testing setup activities	NO/YES	-
9) Presence of testing collateral activity	NO/YES	-
10) Personnel scheduling	CENTRALIZED/ DECENTRALIZED	-
11) Number of suppliers per product	SINGLE/ MULTIPLE	3), 7)
12) Degree of customer relevance	HIGH/ LOW	-

Table 2 - Descriptive variables with the possible outcomes of their assessment

7.14 Framework: *compendium*

CATEGORY	DESCRIPTIVE VARIABLES	GUIDELINE	IMPACT ON (+)(-)
Test process	1. Product modularization.	• If no physical modularization is already in place or the product is not modularized on the base of test modules, then R&D department should be involved. If massive product reengineering is required, a cost/benefit analysis should be performed ("design for testing" approach as a DFx approach). • If the product is already	• Internal Lead Time and Total Lead Time (+) • Fixed Costs if re-engineering is needed (-)

		modularized according to the test modules identified, or a modularization is possible, it should be pursued the delegation of tests on individual modules to the module manufacturer. This would allow possible parallelization and externalization of individual modules tests. The possibility of externalization and parallelization is highly influenced by the variable 2. “Independent test modules”. Variable 3. “relationship with suppliers” also influences this possibility, though to a lesser extent. If the modularization of the existing product implies the R&D department to be involved and massive product reengineering is required, a cost/benefit analysis should be performed (“design for testing” approach as a DFx approach)	
Test process	2. Independent test modules (specific parts of the product whose interconnected functioning is assessed by specific tests that do not involve other parts but the ones defined as test module)	a) If no test modules can be identified, then R&D department should be involved. If massive test reengineering is required, a cost/benefit analysis should be performed. b) If the product is, or can be, composed by interdependent test modules, tests can be split in two parts: 1. tests on individual modules that can be parallelized. 2. ‘system tests’ on the whole system.	• Combined with 1., Total Lead Time (+) • Combined with 1., Outcoming quality (+) • Combined with 1., Recurring Costs (+)

		c) If the product is, or can be, composed by interdependent test modules and there is possibility to develop a simulator to simulate the interface with other test modules, tests can be split in two parts: 1. tests on individual modules that can be parallelized using a simulator to simulate the interface with other test modules. 2. ‘system tests’ on the whole system. Note: in this case tests carried out on individual modules are a higher proportion of total tests compared to the previous option, due to the usage of a simulator. d) If the product is, or can be, composed by independent test modules, tests can be done 100% as individual tests on test modules. Given d) as the ideal situation, product reengineering would be required also in the cases a) b) and c) in order to achieve the complete independence of modules. Also in this case, a cost/benefit analysis should be performed so to assess whether to locally optimize according to the case a), b) and c), or undertaking reengineering in order to achieve the situation presented in d).	
Testing Supply Chain	3. Relationship with suppliers	Current or potential suppliers (in case of module definition that requires evaluating new suppliers) must be classified from a strategic relationship perspective.	• Quality (+) • Combined with 1., Internal Lead Time and

		For all those suppliers that classify for collaborative relationships • Set framework agreements with suppliers. • Adaptation to takt must be asked to supplier when a takt exists. • Modules suppliers should be delegated the modules tests when individual tests can be performed on modules. • For all those functionalities not tested in-house at the supplier's, fixed agreements regarding quality penalties and quality audits should be introduced. Whenever a supplier is identified as 'traditional', the approach must be oriented to maintaining quality of supplies through • Fixed agreements regarding quality penalties and introduction of quality audits.	Total Lead Time (+) • Fixed Costs (-)
Testing Supply Chain	4. number of suppliers per product	• If the suppliers are in number >1 for a single product to be tested (case of modularized product), a centralized milk-run picking from suppliers is suggested in order to eliminate stock and synchronize activities. • If the suppliers are in number =1, no synchronization of pickings is needed. Also the possibility of completely externalizing testing at the supplier's site should be evaluated, compatibly with the result of variable	• Overall testing process efficiency due to synchronization of shipments (+)

		3.“relationship with supplier”. Note that in this case the parallelization of tests on modules can be just given through the utilization of more resources working in parallel.	
Testing Supply Chain	5. Relevance of customers	A Pareto analysis should be performed on the value of customers for the business. • With the 80/20 customers, a collaborative strategy for testing procedure definitions should be adopted. It is important to reach agreements so that once the procedures have been mutually agreed, no extra-tests can be asked by the customer. • With the relatively less influent customers, a predefined set of standard testing procedures should be proposed.	• Total Lead Time (+) • Overall testing process efficiency (+)
Test process	6. Test procedures structure	As for variance reduction approaches, codified written procedures should be set up when not already done for both: • Test activities. • Management of out-of-process activities. • Out-of-process activities themselves , when these can be considered as ‘structured’ according to the correspondent assessment.	• Total Lead Time (+) • Quality (+) • Overall testing process efficiency (+) • Fixed Costs (-)
Test process	7. Out-of-process activities	• If error fixing activities are structured, codification through	• Total Lead Time (+)

		written procedures must be achieved as mentioned in point 6. • If error fixing activities are unstructured, a preliminary assessment has to be carried out considering two variables: o Order of magnitude of number of causes that can be possibly determining each type of error encountered during testing o Number of different people that are possibly involved in the resolution of each type of error The number of possible causes behind each error determines the need for a centralized information sharing about resolution methods, for instance a library of best practices. The number of people possibly involved in the resolution of errors determines the need for an integrated progress-monitoring system that allows specialist personnel to plan specific interventions when needed.	• Overall testing process efficiency (+) • Fixed Costs (-)
Test process	8. Personnel responsibilities	When not already in place, a system of responsibilities attribution should be implemented, for instance with the creation of a "test owner" figure in order to improve quality outputs and motivation.	• Quality (+) • Fixed Costs (-)
Testing Supply	9. Stocks	Ideally no stock should exist.	• Recurrent Costs (+)

Chain		This can be achieved if modules or system shipments are synchronized with the start of testing activities as already mentioned in point 4. An important aspect is the control over suppliers' suppliers. If the company has bargaining power enough to guarantee convenient supplying deals to their suppliers, the intervention should be limited to the intermediation through a framework agreement and not to the direct managing of supplies.	• Overall testing process efficiency (+)
Test process	10. Testing setup	Whenever not done yet, the testing setup (for instance mechanical and electrical wiring, product positioning, etc) should be reduced and optimized by the means of standard Lean tools such as SMED and 5S.	• Internal Lead Time (+) • Fixed Costs (-) • Recurrent Costs (+)
Collateral testing activities	11. Collateral testing activities	Depending on the type of testing process, there could be collateral activities. The general guideline for collateral activities is achieving their link in the process with the core testing activities through a pull flow.	• Internal Lead Time (+)
Test process	12. Personnel scheduling	Personnel scheduling for both testing and collateral activities should be centralized so to guarantee visibility and efficiency in the allocation of resources.	• Overall testing process efficiency (+) • Fixed Costs (-)

Table 3 - Framework graphical representation

7.14 Conclusions

The set of variables deemed of relevance for the description of a testing process have been further described in this section of the Thesis Work from the previously defined ones (section 6).

The Key Performance Indicators of a testing process have been also defined.

Consequently, each variable has been extensively described by including:

- A proposal of assessment method
- A proposed intervention in order to improve the performances of the testing process depending on the value assumed by the specific variable.
- An evaluation of the impact of the proposed interventions over the defined KPIs.

The output of this section is a framework that aims at assessing the features of a specific testing process according to the identified variables and proposing configuration guidelines aimed at improving the process performances, as described in section 7.13.

Section 8: Framework example on a real case

Abstract

This section presents the application of the developed framework on the AS IS situation presented for the case exposed in Section 2.

The section is composed by four main parts.

The assessment proposed by the framework is at first performed on the AS IS situation of Company. The values attributed to each variable are presented, along with their explanation.

On the base of the guidelines suggested by the framework, two reengineered solutions are proposed. The interventions implicated by each solution are punctually described.

The assessment proposed by the framework is then applied to each of the two reengineered solutions in order to appreciate the points of difference.

A comparative analysis of the two solutions on the base of costs, benefits and risks is then summarized in order to justify the choice of one of the two solutions.

8.1 Method

In this section of the Thesis Work, a re-engineering solution is proposed for the process discussed in the AS IS section (section 3.2).

The process re-engineering aims at eliminating those criticalities previously highlighted (section 3.2.6) and analyzed as well as improving the process flow by including the guidelines emerged from the framework assessment (section 7.13). The considerations emerged from the literature analysis will be also taken into account whenever the similarity of the circumstances or the generality of the findings make them applicable in the specific case.

It is important to mention how the specific application of the framework on this case cannot be considered as a validation of the framework. The framework is indeed partially built on considerations made for the AS IS state of this same case and a TO BE state would represent a biased validation. The presented TO BE state therefore simply aims to evaluate the expected benefits deriving from the implementation of the guidelines recommended by the application of the framework on a specific case.

The Authors decided to proceed with the TO BE analysis by performing a scenario analysis in which two alternative solutions are compared with each other and with the base case situation (AS IS state).

This comparison will be based on both qualitative and quantitative aspects.

The TO BE analysis will be structured as following:

- Assessment of the Company's current testing process conditions via the application of the framework (section 8.2).
- Proposal of the two re-engineered solutions (section 8.3).
- Comparison of characteristic features for the three different processes (the two re-engineered solutions and the base case) (section 8.4).
- Comparison of the two proposed solutions with respect to three dimensions: Benefits, Costs and Risks (section 8.5).
- Assessment of the Company testing process conditions under the two re-engineered solutions (section 8.6 and 8.7).
- Conclusions (section 8.8).

8.2 Ranking of the current testing process conditions

1) Degree of product modularization: HIGH.

The product is identified by separate modules that are assembled in order to compose the final system. Modules also would coincide with the test modules, if these were leveraged as mentioned in the following point. It must be highlighted though how the production management logics do not leverage this product modularization, since all the modules of the system have to be entirely manufactured before the modules -as a whole system- can undergo the next production phase. This can be identified as a system batching logic.

2) Degree of identification of independent functional modules: LOW.

The test procedures are structured on the base of partially interdependent test modules; each module represents indeed the object of a test set that can be divided in two subsets, one that does not require the interaction with other modules and another one that does. Nonetheless, the test activities are carried out only when the whole system is in place, not leveraging the partial independence of each module. Therefore this situation represents the equivalent of test modules not being identified.

3) Degree of strategic suppliers' relevance: LOW.

The relationship in place with the sole supplier can be considered as mostly traditional. The relationship is indeed characterized by non specific asset investments and minimal information exchange. Quality issues also arise.

4) Degree of procedure structuring: MEDIUM.

The testing procedures are structured and standardized across the organization. On the opposite, both the management of out-of-process activities and the out-of-process activities themselves are unstructured.

5) Degree of out-of-process activities structuring: LOW.

Error fixing activities are mostly unstructured, with a multitude of interfaces with specialist personnel for errors resolution, and a high number of different causes that possibly determine each error detected.

6) Degree of personnel responsibility: LOW.

The testing operators are assigned the responsibility to personally attempt at first to solve problems on the system undergoing testing whenever an error is encountered. On the other side, though, no personal commitment to the ultimate quality of a module tested is fostered, therefore decreasing considerably the degree of personnel responsibility.

7) Presence of stocks in the testing process: YES.

Stocks are present at the central warehouse as a consequence of both the policy of managing supplies for the first tier supplier and the practice of triggering orders way in advance with respect to the actual date of need of specific material.

8) Presence of testing setup activities: YES.

The testing setup activities are of three types:

- Module positioning
- Powering
- Connection to testing equipment.

The testing set-up activities are not already optimized. An example of this is explained by what stated in the criticalities analysis “wasted motions in positioning”, “dead time between positioning and wiring”, “inefficient wiring activity” and “wasted motions in shipment preparation” (section 3.2.6)

9) Presence of testing collateral activities: YES.

Software development is considered as a collateral activity. The same considerations made above about the low degree of optimization for the testing setup activities can be applied also to the collateral activities (i.e. “long lead time for software development” in section 3.2.6).

10) Personnel scheduling: DECENTRALIZED.

The personnel scheduling is carried out locally per type of activity. No centralized view on the allocation of resources and activity scheduling is currently present.

11) Number of suppliers per product: SINGLE.

The company outsources the manufacturing of modules to a single supplier.

12) Degree of customer relevance: HIGH.

The customer is the principal one for the company in terms of revenues, and it has been acknowledged a high bargaining power due to its business characteristics.

8.3 Graphical representation of the two re-engineered solutions

The application of the framework to the Company’s testing process highlights the presence of some sub-optimal parameters, according to the details provided in section 7.13.

This section will provide the description of two possible TO BE states for the testing process in the Company, re-engineered according to:

- the guidelines proposed by the framework.
- the analysis of the criticalities (section 3.2.6).
- the analysis of the literature whenever the similarity of the circumstances or the generality of the findings make them applicable in the specific case.

In particular TO BE 1 represents the solution characterized by in-house tests activities performance (as it happens in the AS IS case, but with some shrewdness in the testing logic and sequences). TO BE 2 represents the solution characterized by tests entirely carried out on-site at the supplier's.

8.3.1 TO BE 1

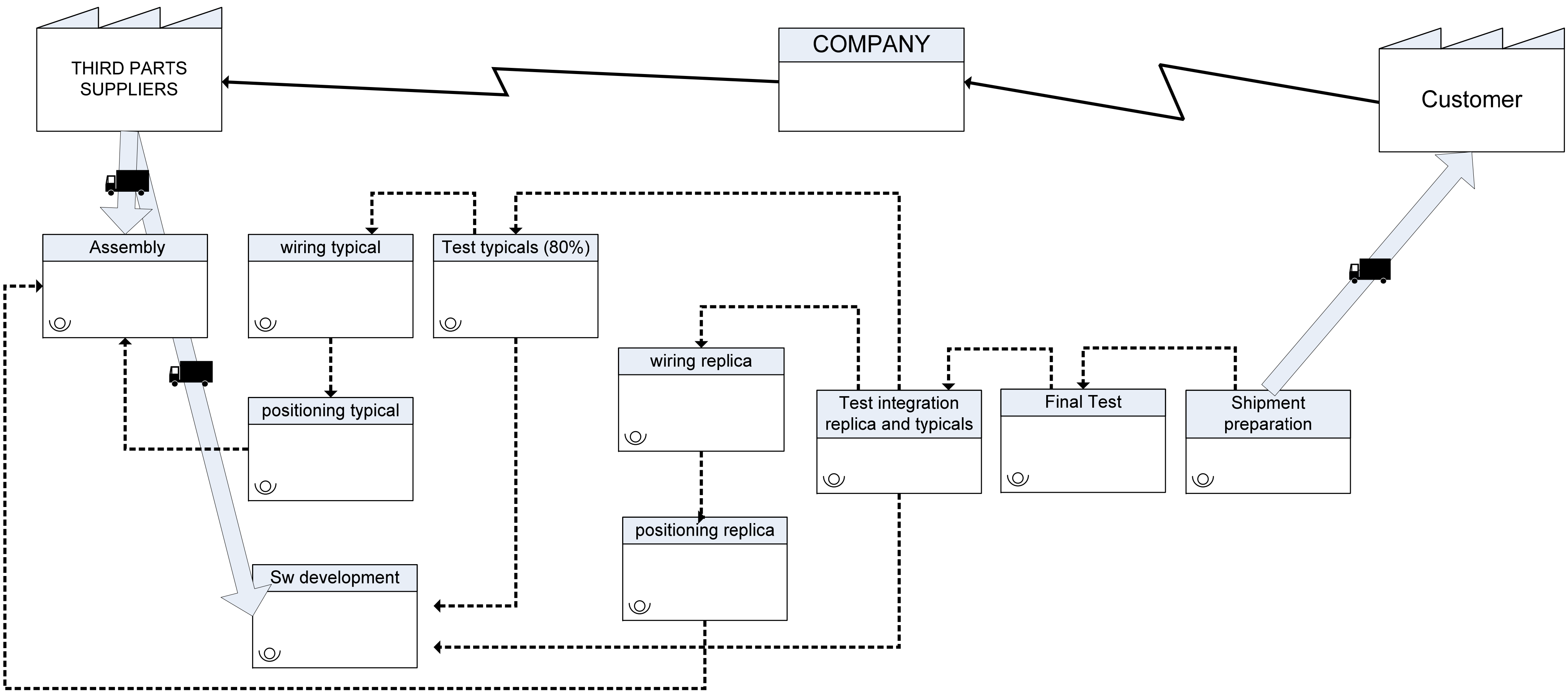

Figure 28 - First re-engineered solution

The previous figure is characterized by the following aspects with respect to the AS IS situation:

- With regards to the presence of stocks within the system, the guideline suggests the pursuit of their elimination.

All the job order materials supplied by the suppliers are now directly delivered either to the module assembler (assembling material) or to the Company (software material) without passing any longer through the transit point.

- With regards to product modularization, the guideline suggests the pursuit of the highest level of modularization that can be achieved. In this sense, a criticality due to production batching logics was previously identified.

The assembly activity is no longer executed according to a batch logic that implies all the modules characterized by the same standard platform being assembled at the same time. The new operative logic is instead based on assembling all the typical modules first independently from the platform type they are assembled on.

- The same can be said for the software development activity, considered as a collateral activity. By leveraging its implicit modularity, the software can be developed separately for the typical modules first, and only at a second stage for the replica ones. The benefits can be identified in:
    - possibility to reuse the software developed and tested for the typical modules for the replica ones.
    - minimization of the risk of local changes having an impact on the whole system (when the changes are made on a typical module while one of its corresponding replica modules is already tested) as it was happening in the AS IS situation due to the fact that testing activities were performed in parallel.

- With regards to the definition of test modules, the guideline suggests to leverage this aspect whenever test modules were not identified.

The testing activity is now performed only on the typical modules at the beginning. This implies performing only a part of the testing procedures with respect to the AS IS situation. By informal interviews with the main actors of the testing activity it is possible to define that the testing procedures that could be executed on a single module with a partial system in place correspond to a portion equal to 80% of the total time needed to test the same module in a condition where the whole system is already in place.

The definition of the above mentioned intervention brings along other two modifications in the testing process:

- While the testing activities are carried out on the typical modules, the module assembler begins the assembly operations for the replica ones and the software developers start customizing the software for the replica.
- Consequently, the replica modules will be delivered to the testing laboratory, the download of the tested software will be carried out and the testing on the whole system can start (the remaining 20% of time needed to test the system functionalities). The whole system is then ready to be delivered to the customer.

8.3.2 TO BE 2

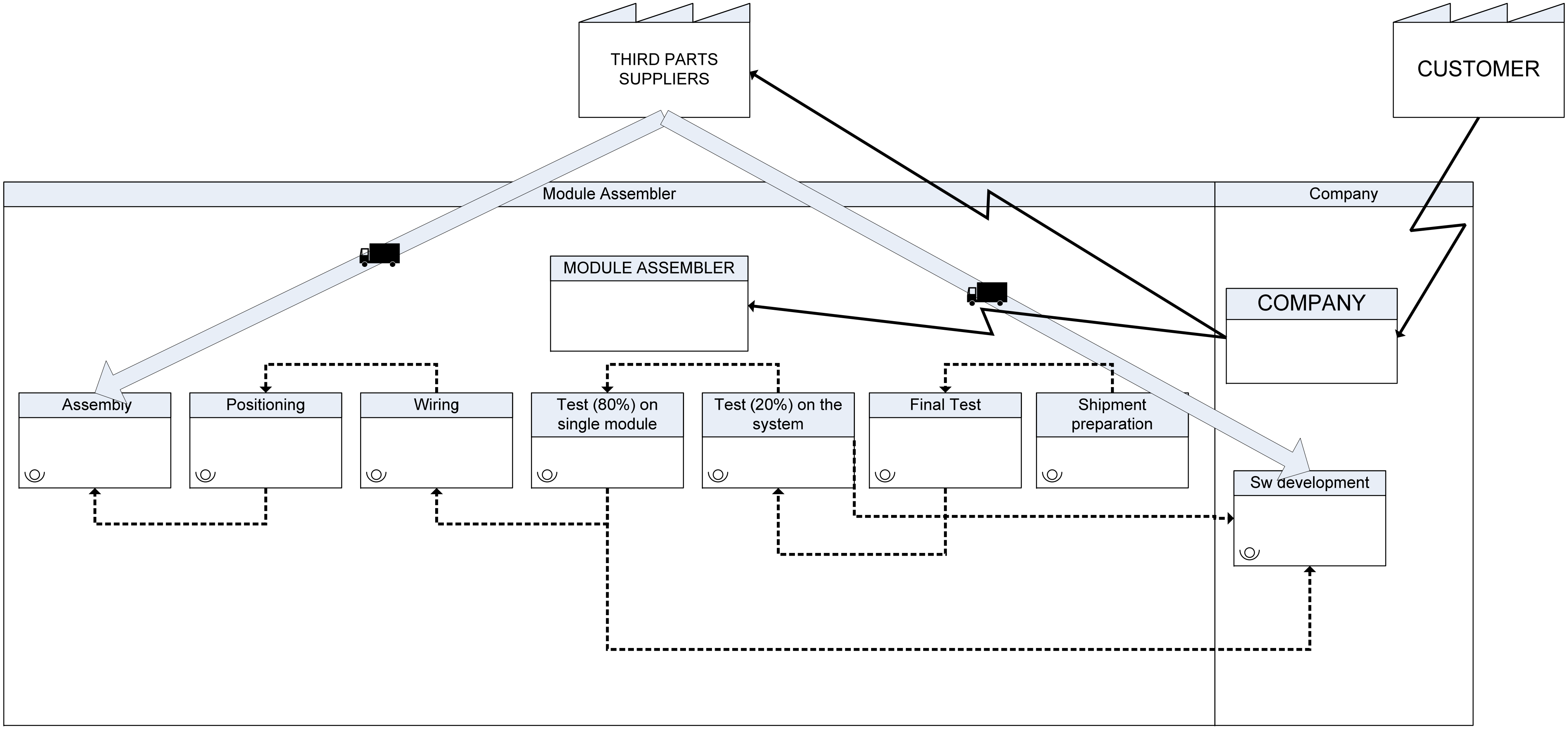

Figure 29 - Second reengineered solution

The TO BE 2 shows a substantial difference with respect to both the AS IS and the first version of the re-engineered process (TO BE 1).

While the test ownership and its relative responsibilities are still Company's duty, with the new configuration the physical location where the tests are carried out has changed. This new organization of the testing process aims at better coping with the issue of quality control. As indeed it emerged from the literature analysis, "the cost of a failure increases dramatically the later it is detected" (Ntafos, 1998). Therefore with the new configuration the testing activities are carried out directly at the module assembler's site in order to minimize the risk of identifying quality problems at later stages and/or in other locations.

Regarding the logic behind the test scheduling, this is similar to the situation explained in the TO BE 1. Although the similarity in the testing logic (80% on a single module and 20% later with the whole system in place), there are some differences with respect to the granularity of the physical object undergoing test.

In particular with this second configuration, we aimed at approaching the ideal "one piece flow" mechanism. In fact, after assembling each module, positioning and wiring it, a big portion of the testing procedures are directly executed on the module.

This procedure is carried out until all the modules of the specific system are partially tested. Afterwards, those functionalities which require the presence of the whole system wired and connected are tested.

The TO BE 2 configuration does not change the software development logic already presented for the TO BE 1 case.

Therefore, the testing activity differs from the TO BE 1 case for the two following characteristics:

- The modules are tested in the same location where they are assembled in order to minimize the costs deriving from defects detected late in the process.
- The test activity is executed on each single module and not on the two subsystem typical /replica.

8.4 Punctual comparison of the testing process characteristics

In order to further detail the punctual interventions proposed for TO BE 1 and TO BE 2, a qualitative table is proposed. Table 4 presents a set of characteristics of the testing process which have been impacted by the proposed re-organization on the rows and the three cases compared on the columns.

Guideline	Characteristic	AS IS	TO BE 1	TO BE 2
Product modularization	Modularity	Yes	Yes	Yes
Externalization of modules test	Unsatisfactory quality	Yes	Possible	No
Supplier's relevance	Test activity infrastructure	Already in place	Already in place	To be predisposed
Procedure structuring	Errors procedures	No	Yes	Yes
Out-of-process activities	Errors management	Unstructured and delocalized	Structured and library-based	Structured and library-based
Personnel responsibility	Module test owner	No	Yes	Yes
Stocks elimination	Warehouse	Yes	No	No
	Software material handling	No	No	1 or 2 handling(s)
Optimization of setup activities	Truck unload and positioning	1	2	0
	Wiring personnel workload	Unleveled	Unbalanced at the modules arrival	Leveled
	Wrapping	2	2	1
	Number of deliveries	2	3	1
	Parallelization of activities	Delay equal to the number of typical modules times their wiring time	Delay equal to the number of typical modules times their wiring time	Delay equal to one typical module times its wiring time
Collateral activities	Software development	Whole system	Module	Module
Personnel scheduling	Testing process personnel	In the Company	In the Company	At module assembler's
Suppliers per product	Number of modules suppliers	Single	Single	Single

Relationship with the customer	Testing procedures	Already established	To be discussed with the customer	To be discussed with the customer
Specific interventions on AS IS criticalities	Customer forecasts	Unreliable	Possibly reliable	Possibly reliable
	Templates	Overlapping	Shared	Shared
	Test procedures execution time	Highly variable	Not variable	Not variable
	Correction on schemes	Inaccurate and not timely	Timely	Timely
	Customer and operator on tests	Operative interference between them	Optimized testing laboratory layout	Optimized testing laboratory layout
	Communication with the customer	Poor	Enhanced	Enhanced

Table 4 - Framework comparison on the case base and the two re-engineered solutions

8.4.1 Product modularization

Modularization

As we stated in section 8.2 the product is already identified by separate modules, therefore it is achieving all the benefits deriving from the product modularization as emerged from the literature overview (section 1.3). Since this parameter has resulted already optimal in the AS IS case, no further interventions are proposed in the two re-engineered solutions with respect to the product modularity aspects.

The only difference lays in the unitary object that moves throughout the testing process. In fact, if in the AS IS case the unit coincides with the whole system (therefore not exploiting the product modularity in the testing activities), in the TO BE 1 solution the unit coincides with the two subsystems (typical and replica modules); in the TO BE 2 solution, instead, the product modularity is leveraged to its maximum extent by considering the single module as the unit.

8.4.2 Externalization of module tests

Unsatisfactory quality

In the section 3.2.6 we highlight a criticality deriving from the level of unsatisfactory quality of modules for some systems coming at the test stage.

Since there is evidence of how "the cost of a failure increases dramatically the later it is detected" (Ntafos, 1998), the main focus during the re-engineering process was kept on trying to remove the sources of bad quality rather than suggesting local improvements.

The quality problems encountered and analyzed were of two types:

- Errors due to the assembly activities.
- Errors in the software configuration.

These two errors were producing a further inefficiency within the testing process due to testing operation logic used in the AS IS case which was aimed at parallelizing the typical module testing with the replica one.

It has happened indeed that while testing a typical module with the customer an error has been detected after a replica module of the same typical had already been tested. This might happen for two reasons:

- The customer asks to perform supplementary tests which are out of the scope of normal procedures (see section 3.2.6 "high variability of test procedures execution").
- The test operator assigned to the replica has not detected the same error because of human error or lesser expertise.

In the TO BE 1 this situation is avoided by assembling and testing the typical modules before any of the replica ones. In this way all the errors possibly detected during the test of the typical modules are fixed before the replicas undergo testing at all.

On the other hand, concerning the errors due to the assembling activity, the TO BE 1 does not improve the AS IS situation.

In the TO BE 2 scenario both types of criticalities are potentially solved. In addition to solving the issue related to software errors, the second solution reduces the assembly problems, their costs and time. Every detected defect can be indeed almost instantaneously removed since the testing activity is performed at the module assembler site as well as the quality inspection activities.

8.4.3 Supplier's relevance

Test activity infrastructure

This infrastructure refers to all the necessary ducts and feeders necessary to cable the modules and power them to then be able to execute the necessary tests.

As it can be inferred, the infrastructure has to be in place where the tests are executed. In both the AS IS case and the TO BE 1 the infrastructure is already in place since the testing area in the first re-engineered solution is the same as in the base case.

In the TO BE 2 scenario, instead, it would require a dedicated investment.

As a consequence, a higher degree of supplier's relevance will be achieved both in the TO BE 1 and TO BE 2 solutions by means of:

- The assembler adaptation to the testing logic and pace.
- An improved communication between the supplier and the Company.

Moreover, in the TO BE 2 solution there is also an investment in the test activity infrastructure at the supplier's site which increases the degree of supplier's relevance as defined in its specific assessment.

8.4.4 Procedure structuring

Errors procedures

As for the testing procedures that are structured and standardized across the organization in the AS IS case, the same evidence cannot be found for the management of out of process activities and the out of process activities themselves.

Therefore the TO BE 1 and TO BE 2 re-engineered solutions attempt at structuring those elements. The proposed solution aims at generating structured procedures for those errors resolution actions that have emerged to be the best practices for that case. This could be done from a library of practices by:

- Information sharing and focus groups initiatives among test operators
- Identification of a best practice for each error resolution among the various ones within the library
- Creation of standard procedures for the identified best practice

8.4.5 Out-of-process activities

Errors management

As mentioned in the AS IS situation, the errors resolution process was mostly unstructured, with multiple interfaces and no systematic sharing of best practices for both error solving and those operative parts that were not covered by procedures (for instance the setting of testing equipment).

Both TO BE 1 and TO BE 2 include the introduction of a structured out-of-process activities management. This would happen via a test activity monitoring system, where all the operators currently performing a testing activity on a module are called to update the information regarding the testing status of a module, including possible errors detected and actions already undertaken in order to solve the error. This would allow both the centralized view of the status of each module and the activity planning for those specialized resources, for instance systems engineers, called to solve an error whenever a solution cannot be found by the operator. Furthermore, this system would allow the creation of a shared library of successful practices that lead to error resolution for each type of error detected.

8.4.6 Personnel responsibility

Module test owner

Both the two re-engineered solutions aimed at increasing the degree of personnel responsibility by assigning full ultimate quality responsibility to the testing personnel. This would be achieved only if all the testing personnel will receive appropriate training over the module testing logics, the possible tests' outcomes and the possible faults resolution methods.

8.4.7 Stocks elimination

Warehouse

Regarding the supplied material flow, it emerged from the AS IS analysis the presence of an intermediate step in the shipping process which was not adding value, but only costs.

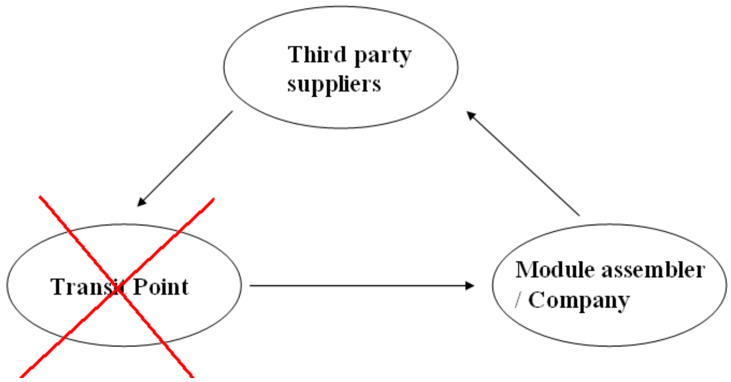

Figure 30 - Company's supplies shipping process

As it can be seen from the Figure 30, the shipping process was so organized:

- Company issued an order to the third party suppliers.
- The third party suppliers delivered the goods to the transit point.
- At the moment of arrival at the transit point, the goods were registered in the enterprise information system and they were re-directed to their final destination: either the modules assembler or Company itself.

As we mentioned in section 3.2.6 ("inventory stagnancy before assembly and software development") orders were placed in great advance with respect to their actual need on their respective sites, therefore implying a cash outflow towards the suppliers well in advance with respect to the same cash outflow if a synchronization of the materials inbound flows would have been matched with the start of the activities. By receiving the goods later, at the moment of their exact request for the start of the subsequent activities, a benefit in terms of postponed financial disbursements to suppliers is achieved.

Moreover, also the stock-keeping cost could be eliminated completely.

In particular we have appraised the following costs items for the management of such a process which therefore are to be considered as savings in both the re-engineered solutions previously presented:

- Stock keeping costs
- Missed opportunity cost due to early order placement and anticipated disbursements
- Removal of ZT preparation and management activity.

Against these savings, in both the TO BE solutions there is the necessity of an investment for the development of a web based tool through which the registration of supplies inbound collection takes place directly at the modules assembler's site.

Software material handling

In the TO BE2 solution the tests are carried out at the supplier's site, while the software development activity is still carried out in-house. Therefore, in order to carry out the test activity there is the need of the job order PCs at the modules assembler's site, and this implies sending the PCs to the supplier once the software is developed.

This peculiarity of the TO BE 2 solution does not bring along any additional cost, since the transport of the PCs to the supplier could be synchronized with the software personnel moving on-site at the supplier's in order to perform the tests.

8.4.8 Optimization of setup activities

Truck unload and positioning

Trucks unload and positioning represent some of the activities needed to prepare the modules for the testing activity. Some considerations can be made regarding the number of times these activities are performed on a single system depending on the selected shipment batching type for the modules composing the system.

In the TO BE 1 these two activities are carried out twice: once for the typical modules first and in a second moment for the replica ones. Therefore the first re-engineered solution adds one activity with respect to the base case.

On the other hand instead, the TO BE 2 solution does not involve any modules transportation since the assembly and test activities are executed at the same physical place.

Therefore, considering the differential costs and times with respect to base case (AS IS) we have:

Scenario	**Impact on time**	**Impact on costs**
AS IS case	Time needed to unload and position the system as a whole	Dependent on the number of trucks needed to deliver the system as a whole
TO BE 1 case	Same as AS IS case	Dependent on the truck load factor (since the typical modules are delivered first

		and the replica ones only in a second moment)
TO BE 2 case	0, no transportation needed	0, no transportation needed

Table 5 – Truck unload and positioning costs and times comparison

Wiring personnel workload

As already mentioned in the paragraph “unleveled work of wiring personnel” of the criticality analysis (section 3.2.6), the wiring personnel, in the AS IS case, works at the maximum of capacity during some phases of the testing process, while it is mostly idle during the test activity itself.

Thus, the wiring personnel workload appears to be unleveled throughout the different phases of the module “lifecycle” within the testing laboratory.

In the TO BE 1 scenario the wiring personnel peaks would be eroded by the lesser number of modules arriving in a single moment and they would be spread out into two peaks with their absolute value corresponding to the percentage of typical modules and replica ones with respect to the total number of modules composing the whole system. The workload of the wiring personnel would be the same during the last phase of the module lifecycle of outbound transportation as in the AS IS case. In fact in the case of the system tested as a whole, the wiring personnel start the shipment preparation activities.

In the TO BE 2 scenario, on the other side, the wiring personnel workload profile is as leveled as possible. In fact, the assembling activity follows the “one piece flow” logic: once one module is assembled and ready to be tested, it is positioned and wired. By following this operative logic, the wiring personnel will have a mostly flattened workload profile during all the modules lifecycle phases, but the last one. As we stated earlier, the system can be prepared for the shipment preparation only once the whole system is tested.

Therefore if we draw a graph where on the x axis is represented the time (and in particular each phase of the module lifecycle) and on the y axis the percentage of wiring personnel workload, the three different scenarios would have the following wiring personnel workload profiles:

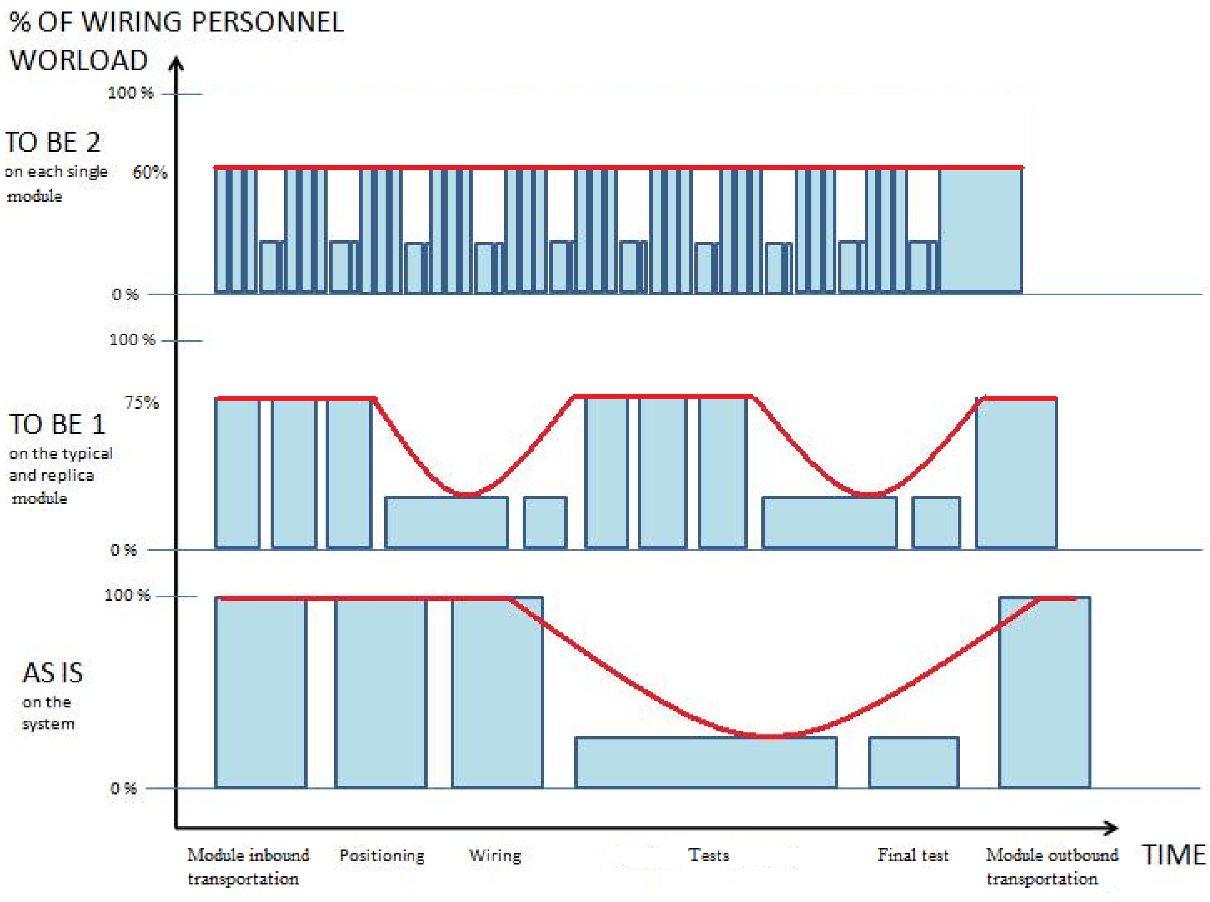

Figure 31- Wiring personnel workload comparison

Wrapping

The wrapping activity is performed twice in the AS IS case. The first time it is performed when the modules are transported from the modules assembler site to the testing laboratory. The second time once the test activity and the final test are successfully completed in order to ship the system to the customer.

The TO BE 1 scenario performs the same way as the AS IS case concerning the wrapping activity. In fact it is performed twice as well.

The TO BE 2 solution, instead, does not prefigure an intermediate transportation from the modules assembler site to the testing laboratory to perform the tests, because the tests are directly executed at the supplier's site. Therefore the wrapping activity is done only once in correspondence with the shipment to the final customer.

Number of deliveries

The same considerations for the wrapping activity can be applied to the number of deliveries for what it concerns the AS IS case and the TO BE 2 scenario. In fact in both cases one delivery corresponds to a wrapping activity.

The same cannot be stated regarding the TO BE 1 solution. In the first re-engineered solution indeed the delivery of the system from the modules assembler site to the testing laboratory is split in two different temporal moments. Therefore the total number of deliveries is three, which corresponds to one extra delivery compared to the AS IS case and two extra deliveries compared to the TO BE 2 solution.

Parallelization of activities

As previously mentioned in the AS IS analysis (section 3.2) some of the stages of the testing process can be parallelized.

In the AS IS situation the activity flow is completely sequential apart from the test activity, which is performed in parallel between typical modules and replica ones even though not in a systematic way (section 3.2.6 "lack of systematic parallelization"). This implies the existence of inefficiencies throughout the testing process (section 3.2.6 "dead times between positioning and wiring" and others).

Therefore in the AS IS situation the delay in the start of test activities with respect to the arrival of the modules in the testing laboratory is equal to the number of typical modules times their wiring time.

The TO BE 1 solution does not improve with respect to the AS IS with respect to the opportunity time and costs, even though it implements corrective actions to overcome some of the criticalities highlighted in section 3.2.6. The test activity is indeed delayed by only the number of typical modules times their wiring time.

This is due to the fact that in both cases the test activities start as soon as the wiring personnel is done with the wiring of modules.

The TO BE 2 solution is designed to overcome the criticalities highlighted in the AS IS case and to perform the different phases of the module lifecycle in the most parallelized fashion. Indeed this solution proposes the test activity to be delayed of just the time needed to wire each single module.

8.4.9 Collateral activities

Software development

In the AS IS case the software development process is performed before the tests begin and the software is entirely developed on the whole system.

In the TO BE 1 and TO BE 2 re-engineered solutions, the modularity of the software development is leveraged. In fact in both caseswe suggest to develop the software first on the typical modules in order to be able to download it on their devices and proceed with the tests on them. While the replica modules are assembled, the software developers extend the software previously developed to include the remaining devices of the system.

8.4.10 Personnel scheduling

Testing process personnel

"Testing process personnel" indicates the professional figures that take part in the testing process.

In the TO BE 1 solution the testing activity is executed in Company's testing laboratory as for the AS IS case. Therefore there are no additional differential costs in the TO BE 1 solution with respect to the base case.

On the other hand, the situation is different for what concerns the solution suggested in the TO BE 2.

The TO BE 2 solution indeed implies that the tests are executed at the supplier's site. Therefore there are some costs and risks involved in this scenario:

- Additional costs derive from the fact that Company's personnel have to be present at the supplier's site to perform the tests. For Company's internal resources, the differential costs with respect to the case base are those related with the personnel transportation to/from the supplier's site for the period corresponding to the duration of their specific tasks execution: the test of the typical modules and the final tests.
- Concerning external resources, Company has to redefine the contractual terms with the resources' suppliers. The redefinition of the contract may represent an additional cost as well as it may not be the case. It definitely represents a risk, though, due to the possibility for the resources' suppliers not to accept the new contractual terms and due to the difficulties to find alternative specialist figures on the market.

8.4.11 Suppliers per product

Sourcing policy

As in the AS IS case where the Company has one supplier, the two re-engineered solutions maintain the same configuration. A single sourcing is therefore kept as the optimal case because of several reasons:

- Difficulty in finding a supplier to certify in the specific business of the Company.
- It would not make sense to purchase different modules of a system from different suppliers because of the system's characteristics themselves. The modules do not require different capabilities for their assembly operations and therefore they do not require the assembling externalization to several suppliers depending on the specific modules (as it happens in TetraPak, as exposed in section 5).

In particular, furthermore, the TO BE 2 solution proposes an investment at the supplier's site therefore making even less convenient a sourcing strategy which implies more than one supplier.

8.4.12 Relationship with the customer

Testing procedures

The testing procedures for the systems object of this Thesis Work have been defined accordingly with a customer in a standard agreement.

Due to stringent quality requirements on the system, the customer proves to be very demanding while performing the testing procedures with the Company personnel.

Both the re-engineered solutions imply reassessing the testing procedures, in order to be able to test the whole system without the need of its physical presence as a whole in the testing laboratory for a part of the testing period.

The testing procedures should be defined taking into account the following necessities during a first phase of the testing activity:

- Testing the typical modules while the replica ones are absent in the TO BE 1 case, or
- Testing a single module's standalone functionalities and devices in the TO BE 2 case.

The system integration functionalities should then be tested once the whole system is assembled and positioned.

8.4.13 Corrective measures on criticalities highlighted in section 3.2.6

This set of corrective actions has emerged from the analysis of the AS IS case and its criticalities (section 3.2.6). Due to their general impact over the performances of the Company and due to their not differential impact depending on the specific re-engineered solution, the proposed solutions for every criticality discussed in this paragraph will be applicable to both the TO BE 1 and TO BE 2 solution.

Customer forecasts

This criticality has emerged as impacting Company, though it is one of those on which the Company has suffered the consequences rather than one that has emerged from an inefficiency inherent in the Company current processes.

In both the re-engineered solutions, it is then suggested to prove to the customer the evidence of the poor forecasts he has provided to the Company. This should be conducted by showing the client, on one side, the inefficiencies arising in the Company from such low reliably information content and, on the other, the benefits he may gain against more reliable forecasts.

The argument can be the one of gain sharing. Company may obtain a gain due to the fact that a more reliable forecast could allow setting up framework agreements with more favorable prices and conditions with the main suppliers. The entity of the gain could be shared with the customer. Only in this way, the customer might perceive a benefit for himself and might start collaborating by providing more reliable forecasts.

Templates

In both the re-engineered solutions, a standard and shared template amongst those users that are requested to make use of it is proposed. Every person should use the same template, therefore not implying the receiver to handle different templates depending on the specific sender’s one. Moreover, it should be avoided that the receiver fills a different template mostly including the same information as the sender’s one.

Therefore a process re-engineering should be carried out starting from identifying the field of information everyone needs, creating clusters of information for which the filling duty has to be assigned to a specific organizational role and defining an order of usage and of recording.

This would allow the Company to benefit from a more structured and more efficient information recording process, while eliminating the time wastes due to the activity duplication.

Test procedure execution time

In the AS IS situation (section 3.2.6) the customer frequently controls the output result of a test and requests additional tests that are not included in the procedure manuals in order to check other functionalities or the same under test but in a more precise fashion.

In both the re-engineered solutions is then proposed to get the customer testing only the procedures that have been agreed on. In fact since the procedures have been mutually agreed by the Company and the customer, this action would just re-establish the rules that have been previously defined and that in the day-to-day work have been relaxed. This action has to be coupled with the modules test procedures redefinition already discussed in section 8.4.12.

Corrections on schemes

In the section 3.2.6 we have highlighted two reasons for such inefficiency. In particular both the re-engineered solutions aim at addressing two corrective actions:

- More coordinate mechanism of information sharing that can be achieved by creating a folder shared among the supplier and the interface who update the files and the drawings in the Company. In particular, the person responsible to make the changes in the drawings within the Company should implement them on paper, scan the file and share it in the common folder. An e-mail indicating that a new file has been uploaded should be automatically generated and sent to the supplier. The same alerting system should be used whenever the supplier executes the modification effectively.
- This web-based tool would allow a more accurate and timely implementation of the corrections. In fact once the supplier has received the drawing to be corrected, he should implement the change, generate a copy to be uploaded and sent to the Company, and use it for the assembling activities of the modules requiring those changes instantaneously.

Customer and operators on tests

As for the AS IS case it has been highlighted an operative interference between customer and operator on tests, in both the re-engineered solutions, instead, we aimed at eliminating such criticality.

In particular, we found out that given the technical requirements of proximity among certain types of modules, a solution which minimized the operative interferences among the several actors working on the system during its tests can be achieved by re-arranging the typical and replica modules on different aisles. This optimal situation can be achieved more or less effectively depending on the relative number of typical and replica modules composing the whole system.

A revised layout which corresponds to such an optimized solution is presented in the following Figure:

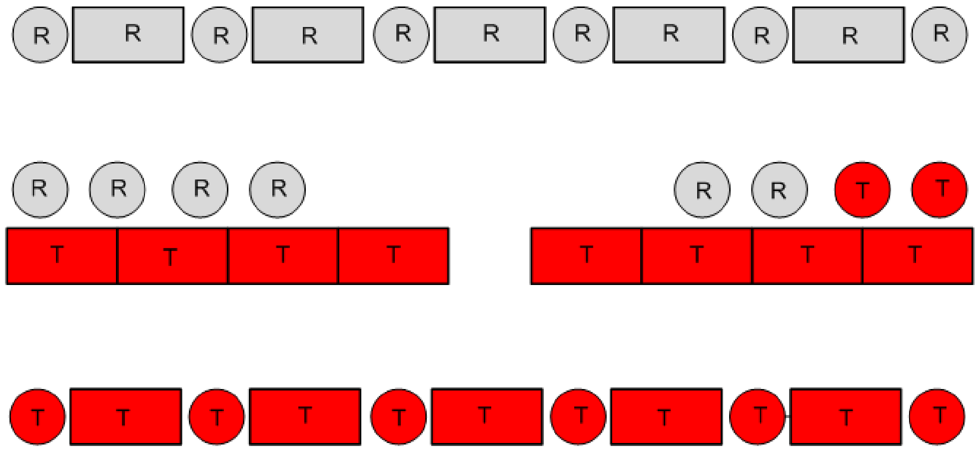

Figure 32 - Optimized system layout

In the presented configuration, the customer will be operating on the typical modules (red boxes and circles) and the Company personnel on the replica modules (grey boxes and circles), therefore minimizing the operative interferences among them.

Communication with the customer

As we previously stated for the variable “unreliable forecasts from customer” also this criticality has emerged as impacting the Company, but it is one of those on which the Company has suffered the consequences rather than one that has emerged from an inefficiency inherent in the Company current processes. Therefore in both the re-engineered solutions a more efficient communication between the Company and its customer has to be set up. If the Company has all the interest in improving the communication with its customer because this would allow avoiding the anticipation of demand and consequent disbursement for materials and external personnel, the Company itself should present the initiative as a win/win situation for the customer. As highlighted in the AS IS criticalities indeed, the customer currently faces the need of scheduling supervisors’ activities for tests on-site at Company’s, and a more efficient communication would benefit a more even distribution of workload.

8.5 Comparative evaluation of benefits-costs-risks of proposed solutions

After exposing the punctual interventions proposed for the two re-engineered solutions, we will now provide a qualitative analysis of the benefits, costs and risks of the two proposed solutions both compared with the base case of the AS IS.

By means of this qualitative analysis we aim at identifying the best re-engineered solution among the two proposed.

Each comparison will be discussed bearing in mind the parameters identified in the framework definition (section 7.13). The variables presented here are the same used to discuss and compare the TO BE 1 and TO BE 2 solutions with the AS IS base case (see table 3).

The punctual analysis has been omitted due to its confidential content which cannot be disclosed for the purposes of this Thesis Work.

	Benefits	**Costs**	**Risks**
Modularity	Not differential	Not differential	Not differential
Unsatisfactory quality	TO BE 2 outperforms TO BE 1	TO BE 1 outperforms TO BE 2	TO BE 1 outperforms TO BE 2
Test activity infrastructure	TO BE 2 outperforms TO BE 1	TO BE 1 outperforms TO BE 2	TO BE 1 outperforms TO BE 2
Errors procedures	Not differential	Not differential	Not differential
Errors management	Not differential	Not differential	Not differential
Module test owner	Not differential	Not differential	Not differential
Warehouse	Not differential	Not differential	Not differential
Job order PCs handling	TO BE 2 outperforms TO BE 1	TO BE 1 outperforms TO BE 2	TO BE 1 outperforms TO BE 2
Truck unload and positioning, wrapping and Lumber of deliveries	TO BE 2 outperforms TO BE 1	Not differential	Not differential
Wiring personnel workload	TO BE 2 outperforms TO BE 1	Not differential	Not differential

Elimination of module positioning supervision	Not differential	Not differential	Not differential
Parallelization of activities	TO BE 2 outperforms TO BE 1	Not differential	Not differential
Software development	Not differential	Not differential	Not differential
Testing process personnel	TO BE 2 outperforms TO BE 1	Not differential	Not differential
Number of modules suppliers	Not differential	Not differential	Not differential
Testing procedure	Not differential	Not differential	Not differential
Tests on typical/replica	TO BE 2 outperforms TO BE 1	TO BE 1 outperforms TO BE 2	TO BE 1 outperforms TO BE 2
Introduction of a “testing monitoring system” software	Not differential	Not differential	Not differential
Stipulation of framework agreements with supplier’s suppliers.	Not differential	Not differential	Not differential
Unreliable forecasts from customer	Not differential	Not differential	Not differential
Overlapping templates	Not differential	Not differential	Not differential
High variability of test procedures execution due to the presence of the customer supervising the process for typical modules.	Not differential	Not differential	Not differential
Correction on schemes not implemented	Not differential	Not differential	Not differential
Operative interference between customer and operator on tests	Not differential	Not differential	Not differential
Poor end communication with the customer	Not differential	Not differential	Not differential

Table 6 - Comparison of benefits-costs-risks between the two re-engineered solutions and the AS IS case

In particular table 6 has the following characteristics:

- Some variables are not differential which means that regardless their specific benefits, costs and risks they have the same impact on the AS IS case. Therefore they do not represent variable which will discriminate in the choice of the more optimized re-engineered solution.
- Some variables represent a trade-off between the benefits and the costs and risks involved. In fact the solution which brings about greater benefits is also the one which has higher costs and bears the higher risks.

As it can be inferred from the Table 6 the TO BE 2 solutions presents greater benefits with respect to the TO BE 1. On the other hand, though, the TO BE 1 solution presents lower costs and lower risks than the TO BE 2 solution.

Nonetheless, the analysis performed on the base of quantitative values that cannot be disclosed due to confidentiality reasons highlighted that the TO BE 2 solution has to be preferred to the TO BE 1 solution. Benefits appear indeed to grow more than proportionally with respect to costs in the TO BE2 solution compared to the TO BE 1. TO BE 2 therefore represents the solution we suggest as a proposal for process reengineering.

8.6 Ranking of the TO BE 1 testing process

1) Degree of product modularization: HIGH.

The product is identified by separate modules that are assembled in order to compose the final system. Modules in this case coincide with the test modules, if these are leveraged as mentioned in the following point.

From an operational standpoint, the substantial difference between this case and the AS IS one lays in the unitary object moved throughout the flow. While in the AS IS case the unit coincides with the whole system (software development, assembly, transport and test performed on the system as a whole), in TO BE 1 case the unit is the typical group at first, and the replica group then (with decoupled software development, assembly and transport phase and partially decoupled testing phase).

2) Degree of identification of independent functional modules: MEDIUM - LOW.

The test procedures are structured on the base of partially interdependent test modules; each module represents indeed the object of a test set that can be divided in two subsets, one that does not require the interaction with other modules and another one that does. The partial independence of each module is now leveraged.

3) Degree of strategic suppliers' relevance: MEDIUM.

The relationship in place with the sole supplier can still be considered as traditional to some extent. In this case, though, some collaborative initiatives are introduced and the quality issue is jointly addressed.

4) Degree of procedure structuring: HIGH.

Compared to the AS IS situation, both testing activities and management of out-of process activities are now structured.

5) Degree of out-of-process activities structuring: HIGH.

The introduction of a test activity monitoring system forces the introduction of a procedure for the management of out-of-process activities.

6) Degree of personnel responsibility: HIGH.

The introduction of a test activity monitoring system makes the test operator responsible for the progress and the update of tests on the module he is currently operating on.

7) Presence of stocks in the testing process: NO.

The central warehouse is removed and the material shipments are synchronized with the actual moment needed for the correspondent activities to start.

8) Presence of testing setup activities: YES.

The testing setup activities have been optimized from the AS IS situation, also achieving a parallelization between the positioning and wiring phases. The workload of personnel has also been smoothened during this phase.

9) Presence of testing collateral activities: YES.

Software development is considered as a collateral activity. The parallelization of software development is achieved to the maximum extent allowed by the software composition. This allows the allocation of a shorter time slot to the development of software for each single system, therefore.

10) Personnel scheduling: CENTRALIZED.

The introduction of a test activity monitoring system allows centralized up-to-date control over the progress of testing operations and allows personnel allocation and activity scheduling on the base of continuously updated information.

11) Number of suppliers per product: SINGLE.

The company outsources the manufacturing of modules to a single supplier.

12) Degree of customer relevance: HIGH.

The customer is the principal one for the company in terms of revenues, and it has been acknowledged a high bargaining power due to its business characteristics. In this case, though, the company is partially sheltered from disruptions arising by the customer imposing extra-testing procedures through the mutual agreement of fixed procedures prior testing.

8.7 Ranking of the TO BE 2 testing process

1) Degree of product modularization: HIGH.

Analogously as TO BE 1, product modules are identified.

From an operational standpoint, the substantial difference between this case and the AS IS and TO BE 1 lays in the unitary object moved throughout the flow. In the AS IS case the unit coincides with the whole system (software development, assembly, transport and test performed on the system as a whole); in TO BE 1 case the unit is the typical group at first, and the replica group then (with decoupled software development, assembly and transport phase and partially decoupled testing phase). In this TO BE 2 case, the unit is the individual module (with decoupled software development and assembly, and partially decoupled testing phase).

2) Degree of identification of independent functional modules: MEDIUM - LOW.

Analogously as TO BE 1, the partial independence of each module is now leveraged. It has to be noted how in any case the degree of independence achieved with this solution is higher compared to the TO BE 1 solution. In this case, indeed, a certain portion of the total tests is carried out on standalone modules without the remaining ones composing the system. In the TO BE 1 solution, the same was performed on typicals at first and on replicas in a second moment, therefore leveraging the modularity to a lesser extent.

3) Degree of strategic suppliers’ relevance: HIGH.

The relationship in place with the sole supplier can now be considered as collaborative, characterized by specific asset investments, significant information exchange, and integrated technological and functional systems across the firms.

4) Degree of procedure structuring: HIGH.

Compared to the AS IS situation, both testing activities and management of out-of process activities are now structured.

5) Degree of out-of-process activities structuring: HIGH.

The introduction of a test activity monitoring system forces the introduction of a procedure for the management of out-of-process activities.

6) Degree of personnel responsibility: HIGH.

The introduction of a test activity monitoring system makes the test operator responsible for the progress and the update of tests on the module he is currently operating on.

7) Presence of stocks in the testing process: NO.

The central warehouse is removed and the material shipments are synchronized with the actual moment needed for the correspondent activities to start.

8) Presence of testing setup activities: YES.

The testing setup activities have been optimized from the AS IS situation, also achieving a parallelization between the positioning and wiring phases. The parallelization of setup activities is further leveraged in this case due to the fact that activities are carried out on single modules independently rather than batching typicals/replicas as in the TO BE 1. The workload of personnel has also been smoothened during this phase.

9) Presence of testing collateral activities: YES.

Software development is considered as a collateral activity. The parallelization of software development is achieved to the maximum extent allowed by the software composition. This allows the allocation of a shorter time slot to the development of software for each single system, therefore allowing a single scheduling point for testing and collateral activities.

10) Personnel scheduling: CENTRALIZED.

The introduction of a test activity monitoring system allows centralized up-to-date control over the progress of testing operations and allows personnel allocation and activity scheduling on the base of continuously updated information.

11) Number of suppliers per product: SINGLE.

The company outsources the manufacturing of modules to a single supplier.

12) Degree of customer relevance: HIGH.

Analogously as before, the company is partially sheltered from disruptions arising by the customer imposing extra-testing procedures through the mutual agreement of fixed procedures prior testing.

8.8 Conclusions

The framework has been applied to the AS IS situation of the testing process presented as the main case study.

The assessment has brought to evidence the presence of a set of suboptimal variables according to the framework.

Two re-engineered solutions for the testing process on the base of the framework guidelines have been proposed.

A measurement of the testing performance indicators (time, cost, quality) of the two reengineered solutions identifies a general improvement with respect to the AS IS situation.

Particularly, the re-engineering proposal that leverages the concept of modularity to a higher extent (TO BE 2) appears to be the one with the greatest performance improvements, although it also represents the solution with higher requirements in terms of dedicated investments and greater possible risks.

Section 9: Framework validation

Abstract

This section presents the results of the validation for the developed framework.

The framework has been proposed to a set of companies conforming to a series of characteristics in order to assess its validity and robustness, and to identify possible pitfalls and hotspots where to address improvement efforts.

This section is organized into three main parts.

The validation method is presented, along with the set of companies chosen to perform the validation campaign and their distinctive features.

The results of the validation campaign are then presented; strengths, weaknesses and possible extensions are here discussed.

Last, a generalization is proposed by considering the impact of some new variables emerged during the validation on the guidelines proposed within the framework.

9.1 Validation campaign

The developed framework has been proposed to a series of companies with the aim of validating the content and its applicability.

Each validation has been carried out by the means of interviews on-site at the specific company with either a Chief of Operations or a Quality Manger.

The validation method was composed of two macro parts:

- Proposition
  - Assessment of the company on the base of the framework variables.
  - Proposition of the guidelines suggested by the framework on the base of the assessment.
- Feedback
  - Punctual feedback of the interviewee on the benefits of the proposed guidelines in the context of the company.
  - Assessment of constraints that would prevent the company to adapt to the specific guidelines.

  - Assessment of perceived exhaustiveness of the identified descriptive variables and perceived relevance of the same for the specific operative context.

A set of five companies has been considered in order to perform the validation campaign, namely:

- Arol S.p.A. – Canelli (AT) Italy – May 26th, 2010.
  - Operation manager: Mr. Barbieri.

- TTT S.p.A (fictitious name) – May 28th, 2010.
  - Operation manager: Mr. A.R.

- SEW EURODRIVE Ltd. – Solaro (MI) Italy – June 8th, 2010.
  - Operation manager: Mr. Di Francesco.

- SSS S.p.A (fictitious name) – June 10th, 2010.
  - Operation manager: Mr. G.N.

- GEA PROCOMAC S.p.A. – Sala Baganza (PR) Italy – June 10th, 2010.
  - Quality manager: Mr. Ferrarini.

All these companies present the characteristic of performing an internal testing process on their product/system.

A classification of the chosen companies can be provided along different drivers. Different positioning along the drivers generated a diversification within the sample; this diversification was reflected in the outputs of the validation campaign, as explained in the results section.

The chosen companies can therefore be discriminated according to:

- Industry. All the companies operate in manufacturing. Two of the chosen companies belong to the bottling machines manufacturing industry, one belongs to the packaging machines manufacturing industry, one belongs to the capping machines manufacturing industry and one belongs to the gearmotors manufacturing industry.
- Type of assembly performed internally. The constraint on the characteristic of outsourced manufacturing, as for our definition of testing process (section 1.2), has been relaxed in

order to include companies that could provide possible hints for the extension of the framework to cases where the testing process comes downstream of an internal assembly process.

- Lean implementations. Two of the companies considered operate according to Lean methodologies, two are currently undergoing the implementation and one is still operating according to traditional manufacturing approach.

The results of the validation campaign are presented in the following paragraphs.

9.2 Results

9.2.1 Framework validity

An overall general validity has been acknowledged by the interviewees to the framework.

Particularly:

- The descriptive variables have been acknowledged as relevant for the description of the essential features of a testing process.
- The guidelines proposed have been acknowledged as coherent with the descriptive variable they refer to. Also their potential effectiveness in terms of process optimization has been proved by either:
  - ongoing initiatives aligned with the guideline (Arol, GEA, SEW).
  - or interest in the possibility of implementing initiatives aligned with the guideline (TTT, SSS).

The validation campaign brought to evidence the bundle of variables related to product and tests modularization as the core of the framework; this has generally been acknowledged as the crucial point where the most criticalities related to a test process and the most radical opportunities for improvement arise.

The reengineering actions underpinning the efforts for achieving modularization mostly involve interactions with the R&D and technical departments; a hotspot has been identified in the complexity of interactions and entity of investments required to develop this kind of initiatives, which might not be offset by the benefits.

Second to the "modularization bundle", the assessments and guidelines related to the generation of procedures for testing and out-of-process activities, and the attribution of responsibilities within the test personnel are acknowledged as of interest. Particularly, the aspects related to the attribution of responsibilities related to the quality outputs are acknowledged as of higher interest within those companies that are already undergoing a Lean implementation with focus on TQM (Total Quality Management) aspects.

Also, the assessments and guidelines related to customers and suppliers are identified as of interest. The implementation of these guidelines is nonetheless often seen as constrained by current supply chain conditions. This is particularly true for those companies whose customers are characterized by high bargaining power and whose suppliers are characterized by distinctive core skills that are hardly replaceable.

Some weaknesses and opportunities for improvement have also been attributed to the framework.

The operations manager at Arol SpA has identified an interest in the possible inclusion of a guideline concerning the entity and timing of involvement of the customer in the definition of testing procedures with respect to the product lifecycle. Generally speaking, this could be of interest in the context of highly customized products, where the constraint of the customer's requests is perceived as more stringent than other more standardized realities.

Another point of improvement comes from the Quality Manager of GEA PROCOMAC SpA. The company currently implements the practice of establishing a temporary pool of experts for the definition of customized test procedures depending on the type of product that needs to undergo testing. The definition of these procedures includes creating a list by picking from a standard pool of tests available; this is done downstream of a risk assessment on the specific product, so that each and only necessary test is included in the list. The list is then prioritized, ranking first those tests aimed at ensuring those functionalities that bring along the highest component of risk for the product. This practice is of interest to be further explored in order to possibly include it within the set of guidelines proposed.

Other comments were related to the fact that some descriptive variables tend to lose significance in some contexts. Namely:

- The variables related to supply chain ("number of suppliers per product" and "degree of supplier's strategic relevance") can lose significance whenever the specific context detaches from the characteristics of a testing process as we defined it (see section 1.2); this happens for instance in the case of companies performing a product assembly in-house that goes beyond the assembly of ready-made modules for testing purposes.

  Furthermore, the variable relative to the presence of stocks in the system can get a different meaning in this case, since the presence of stocks can refer to components and parts for assembly, and not only to materials directly related to testing.

- The specific variable “number of suppliers per product” is also identified as not relevant for a company operating in a market characterized by a highly customized demand, where keeping multiple suppliers per type of modules is considered as a strategic choice.
- The specific variable “presence of testing setup activities” has been acknowledged as of minor importance with respect to the others due to the simplicity and relatively low impact of setup activities in the cases considered for the model validation.

Together with the punctual comments described above, a series of more complex considerations have emerged from the validation campaigns. These are described in detail as they represent points that have not been considered within the framework and that could be worth further investigation in order to derive more tailored guidelines.

- **Subsystem as a complex system.** From the validation campaign it has emerged that an important constraint to the applicability of the framework originates from the type of product/system under analysis.

A loss of significance is indeed appraised whenever the functional architecture of the product is rather simple; this is the case where the identification of product modules would coincide with simple mechanical parts or subassemblies.

This is for instance the case identified by the Chief of Operations within SEW EURODRIVE for the ‘reducer’ product type. The product itself is a mechanical device where modules are represented by a certain number of parts aggregated into subassemblies, whose interoperability is of mechanical type. There is indeed a lack of significance for tests to be carried out on the individual subassemblies, besides a tolerance inspection, due to the fact that the functionalities of interest to be tested for each single subassembly emerge only in a context of complete product assembly.

There is a plurality of assessment variables and consequent guidelines that are affected by this peculiarity. The variables “product modularization” and “independent test modules” jointly appear to be the most influenced ones. Due to the above discussed coincidence of modules with mechanical subassemblies, no tests are actually of significant value on the individual modules until they are assembled into the final product. This implies a lack of validity for the guidelines proposed for “independent test modules”. Concerning “product modularization”, the proposed guideline of pushing on product modularity is acknowledged in this case a certain value, even if not from a testing standpoint. The re-organization of the product architecture in this case would take place through the creation of a broader layer of subassemblies in between the components and the finite product layers. This would ease the assembly operation itself, but it would not represent a breakthrough from a testing standpoint.

- **Multiple modularity levels.** From the validation campaign it has emerged that product modularity can be evaluated on multiple levels; this aspect has not been made explicit in the context of the assessment on “product modularization”.

This issue has been brought along by the interviewees within the packaging and filling machines manufacturing companies considered for the validation. In all those cases, product modularization could be identified at different architectural levels, with different characteristics. For the sake of generalization, we can refer to “system module”, or machine, and “machine module”. In general, the final product for all these companies is indeed a “line”, or system, which means an integrated set of machines disposed in a defined sequence in order to respect the priorities of operations that need to be performed. Each machine within the line represents a line’s module. Furthermore, each line’s module can present a further modular architecture, where a series of interoperating modules guarantee the functionalities of the final assembled line’s module.

A difference has been highlighted in terms of possibilities of approaching modularity at different levels. In general, multiple and more complex interfaces exist among machine modules, while a more linear relation, and generally of the type ‘input/output’, exist between line’s modules.

The interviewees generally point at machine module identification as the most problematic of the two; it indeed most often involve re-engineering and subsequent costs, on the opposite of line’s modules, which are usually conceived and designed already as individual modules part of a line.

The guidelines proposed for the assessment on “independent test modules” are therefore of easier implementation concerning line’s modules rather than machine modules, where a possible product reengineering with subsequent investments is involved.

Generalizing outside the scope of the specific product and industry, cumulative benefits can be obtained from a testing standpoint by leveraging modularization on different levels of the product architecture. Particularly, whenever modularization is already embedded in the product design, it is possible to directly focus the efforts on tests parallelization and externalization, plus coordination of the supply chain. At a lower level in the product architecture, as opposite, it might be necessary to focus the primary efforts on the physical identification of modules before undertaking all the actions mentioned in the previous case; furthermore, due to complex interfaces, the definition of individual test modules can be of a higher complexity compared to the previous case.

The identification of different levels of modularity can also allow a prioritization of the interventions suggested within the framework, so to schedule first those interventions characterized by lower costs/risks or schedule only those interventions whose benefits outweigh the costs.

- **Volume and variety.** The validation campaign has highlighted an impact of volumes and variety characterizing the situation under analysis on the convenience of product modularization.

In a few of the companies assessed for the validation, a predominant characteristic of the production system was the high product variety managed; this is often the consequence of a marketing choice aimed at serving markets where customization becomes the order winner.

In those cases where variety is higher and the product customization can reach the lowest levels of the product architecture, the definition of product modules becomes inconvenient, since that would bring along a certain degree of rigidity in the system.

In the case of SEW EURODRIVE, for instance, the product architecture of the 'gearmotor' product type identifies only a few simple subassemblies, while for its major part the product is composed by individual mechanical components assembled one by one on the final product. This situation is due to the high customization, also at components level, offered to the customer. As the Chief of Operations highlights, if the company was operating by offering a few standard product types, as most of their competitors do, there would undeniably be a convenience is pushing on modularity; ideally, two high-level modules (motor and reducer) could be identified and tested separately. In their case, nonetheless, achieving modularity would bring along an inflexibility that would hardly be justified by the possible benefits achieved in the testing phase.

Furthermore, as comprehensible, the volumes significantly impact on the appeal of investing on developing simulation tools for testing. Wherever the business runs on a few product or system units per year, the investment would be hardly justified, as for the observations of the two managers operating in the packaging machines industry, where volumes are of the order of less than twenty units per year.

- **Complexity and number of modules interfaces.** The validation campaign has highlighted an impact of complexity and number of modules interfaces on the ease of generating standalone tests on individual modules.

We can consider for instance the case of bottling machines in comparison with Tetra filling machines. In both cases, the line's modules present interfaces on the input side with a block providing the liquid to be packaged or bottled. Bottling machines, on top of that, present an interface with a block feeding bottle to be filled with the liquid; in the case of Tetra filling machines, the package is generated within the same module that fills it, therefore no upstream interface with a package feeder is present.

This distinction brings along a significant difference in terms of possibility for standalone tests. In the case of bottling machines, there is no evident convenience in running a completely standalone test on the filling module since that would require the presence on-site of a complex bottle-feeder that provides bottles as input to the filling module. On the opposite, standalone tests are currently carried out on Tetra filling machines due to the absence of this interface to be simulated: the module is fed with the packaging material and a complete production run can be therefore simulated without any need for an external complex feeder.

Generalizing, it is evident how the complexity and the number of interfaces among modules impact on the investment efforts needed in order to enable standalone tests. Depending on the degree of complexity of the interfaces, therefore, the benefits arising from test modularization might not outweigh the costs.

The validation campaign highlighted an overall general validity of the framework.

The identified variables have been acknowledged significance for the description of a testing process, even if to different extents.

Two points of improvement have been identified and four variables have been acknowledged a loss of validity depending on the specific operating context of the company.

Four open points are also identified. These are related to characteristics of the specific product or production system that have not been taken into account and that are worth additional investigation in order to further tailor the indications provided within the framework.

The open points are:

1. Subsystem as a complex system
2. Multiple modularity levels
3. Volume and variety
4. Complexity and number of modules interfaces

And they are further explored within the following paragraphs.

9.2.2 Framework extension

The results of the validation campaign allow a refining of the presented framework.

From the framework refining standpoint, two are the important inputs deriving from the validation campaign:

- Ranking of proposed areas of intervention in terms of potential benefit on the test process performances.
- Identification of variables that have not been considered within the framework and that could be worth further investigation in order to derive more tailored guidelines.

Five variables are identified as the ones that could be possibly explored:

1. Subsystem as a complex system.
2. Multiple modularity levels.
3. Volume and variety.
4. Complexity and number of modules interfaces.
5. Type of assembly performed internally; particularly, this last point emerges from the relaxation of the outsourced production constraint defined for the test process as we consider it.

As for the proposed areas of interventions, three are identified as of very high or high relevance:

- Modularity (variables “product modularization” and “test modules”).
- Supply Chain (variables “degree of strategic supplier relevance”, “number of suppliers per product” and “degree of customer relevance”).
- Test Procedures and Personnel Empowerment (variables “degree of procedure structuring”, “degree of out-of-process activities structuring” and “degree of personnel responsibility”).

Each of the additional variables identified can be integrated in the framework by considering how the guidelines could be modified and tailored on the base of the new specific variables identified. For the sake of relevance, we are just going to consider the impact on those variables that have been identified as relevant.

In order to perform the analysis, it is useful to cluster the existing guidelines according to a double driver: relevance (whether the guideline has been deemed relevant) and impact (whether the guideline is impacted by the new variables). A graphical representation is presented in Figure 33.

relevant + not impacted	**relevant + impacted**
• "degree of procedure structuring" • "degree of out-of-process activities structuring" • "degree of personnel responsibility"	•"degree of product modularization" •"degree of identification of test modules" •"degree of strategic supplier relevance" •"number of suppliers per product" •"degree of customer relevance"
not relevant + not impacted	**not relevant + impacted**

Figure 33- Variable cluster on the base of relevance and impact

The guidelines that have not been deemed relevant are not further taken into account; their formulation refers to the original one presented within the framework.

The guidelines that have been deemed relevant but are not impacted by the new variables are here re-proposed with no modification from their original formulation presented within the framework.

The guidelines that have been acknowledged relevance and are impacted by the new variables are here re-proposed and tailored on the base of the new variables.

In the following paragraphs each new variable is considered along with the tailoring for those guidelines identified as "important+impacted".

1. **Subsystem as a complex system.**

    - If the subsystem, or module, is again a complex system, it is possible to consider *in toto* the guidelines proposed for "product modularization" and "test modules". Therefore the guidelines suggest:

    - Modularizing the product on the base of the identified complex sub systems.
    - Seek for test modularity to the maximum possible extent, with the situation of standalone tests as the ideal one. In case of a suboptimal situation, consider R&D intervention for re-engineering whenever the benefits outweigh the costs.
    - Leveraging the product and test modularity by externalizing tests to the module manufacturer and parallelize tests on multiple modules.

- If the subsystem, or module, is not a complex system then two situations can arise for which the guidelines need to be re-dimensioned independently from the single occurrence:
    - If the subsystem is for instance a single component
        - No standalone functionalities are generally performed by a simple component; therefore there is no requirement for testing on it outside the final assembled product or system. Tolerance controls on mechanical parts and visual inspections could eventually be the quality controls performed on the individual module.
    - If the subsystem is for instance a small mechanical subassembly
        - Few standalone functionalities are generally performed by a subassembly; therefore it should be evaluated the possibility to test its functionalities outside the final assembled product or system. Furthermore, in case of positive outcome from the previous evaluation, it needs to be ascertained whether the benefits outweigh the costs to proceed with standalone tests.

2. Multiple modularity levels.

- If modularity is identifiable in the system or product on multiple levels, it is suggested to prioritize the interventions indicated (seeking for test modularity and leveraging it by externalizing and parallelizing tests on individual modules), so to schedule first those interventions on the module levels characterized by lower costs/risks, or schedule only those interventions whose benefits outweigh the costs.
- If modularity is identifiable in the system or product on a single level, the approach to the realization of interventions as proposed in the case of multiple levels cannot be applied. It is therefore necessary to proceed with the guidelines for product and test modularization, externalization and parallelization on the single module level identified, prior assessing that the benefits identified outweigh the costs.

3. Volume and variety.

- A combination of low volumes and high variety poses a significant limit on the benefit of those guidelines implicating investments in product re-engineering and involvement of R&D department. Both the investments in a product re-engineering oriented towards modularization and in the development of simulation tools in order to decrease the inter-dependability of modules tests would indeed be hardly justified by low volumes and high product customization; high product customization makes indeed the identification of standard modules a possible point of disadvantage. The guideline in this case suggests:
  - Endeavor in achieving the maximum degree of test modularization that does not imply either investments in simulation tools or product re-engineering (case 2. proposed for the assessment on “independent of test modules” in section 7.3).
- A combination of high volumes and low variety represent a significant precondition for investments in developing simulation tools and product re-engineering to be outweighed by the benefits. Therefore the guidelines suggest:
  - Modularizing the product on the base of the identified complex sub systems.
  - Seek for test modularity to the maximum possible extent, with the situation of standalone tests as the ideal one. In case of a suboptimal situation, consider R&D intervention for re-engineering whenever the benefits outweigh the costs.
  - Leveraging the product and test modularity by externalizing tests to the module manufacturer and parallelize tests on multiple modules.

4. Complexity and number of modules interfaces.

- The presence of simple interfaces among modules represents a potential precondition for the benefits of developing a simulator to outweigh the costs. The guideline in this case suggests:
  - Endeavor in achieving the maximum degree of test modularization allowed by the development of simulation tools (case 3. proposed for the assessment on “independent of test modules” in section 7.3), or product re-engineering when a cost/benefit analysis highlights an opportunity in doing so.
- The presence of complex interfaces among modules potentially implies higher costs of development for simulation tools, as opposite to the case above. The guideline in this case suggests:

- Endeavor in achieving the maximum degree of test modularization that does not imply either investments in simulation tools or product re-engineering (case 2. proposed for the assessment on “independent of test modules”).

5. Type of assembly performed internally.

- If assembly operations are performed internally, a limitation is imposed on the standard guidelines proposed. By performing assembly activities internally, there is a lack of opportunities for tests to be externalized and parallelized by concurrent execution of modules tests at the suppliers’ sites. In this case a possible guideline would be:
  - Assessing whether the benefits outweigh the cost for a parallelization of testing to be achieved through the utilization of more resources performing tests concurrently on different modules. This is most likely to be the case when Test Lead Time is the key performance indicator.
- If assembly operations are not performed internally, the guidelines proposed still hold valid as:
  - Leveraging the product and test modularity by externalizing tests to the module manufacturer and parallelize tests on multiple modules. In this case, unless single sourcing is done for all the modules composing a system, no need of extra resource is incurred in order to guarantee test parallelization on individual modules.

The identified open points have been investigated in order to further tailor the indications provided within the framework.

The impacts of considering these open points have just been assessed for those variables that have been identified as significant during the validation phase.

The variables have therefore been divided in four clusters according to two drivers: “importance” (emerged from the validation) and “impact” (due to considering the open points).

The indications corresponding to variables assessed as “important but not impacted” have been recommended without any particular tailoring made on the base of the open points.

The indications corresponding to variables assessed as “important and impacted” have been tailored on the base of what emerged during the validations as open points.

The result is a further refining of some indications provided within the framework on the base of specific business characteristics.

This constitutes a relaxation in the assumption made during the development of the model that a single best practice exists for each of the identified variables. The validation and further developments have demonstrated indeed that the indications can be tailored on the base of different business characteristics, and therefore no absolute best practice can be identified.

9.2.3 Conclusions

The value of the developed framework in the context of real world applications has been appraised on the base of the results from the validation campaign.

From the perspective of a customer seeking for a methodology to approach a performance improvement initiative on its testing process, the developed framework represents a good *compendium* of the most significant variables characterizing the testing process that could represent direct levers for improvement.

Furthermore, the framework represents a comprehensive exploratory tool that allows considering the available options on the process levers and their combined effects. Also, the specific business characteristics of the customer are taken into account by tailored guidelines.

Therefore, the framework proves to be an interesting tool for a manufacturing company considering the opportunity of improving the performances of its testing process. The tool is of interest for companies performing a final test on products/systems whose manufacturing is mostly outsourced, and, though to a lesser extent, to companies with internal manufacturing activities.

The framework therefore represents a handy tool in order to perform an analysis of performance improvement opportunities within a testing process. Sticking to the tool ensures that the most relevant improvement levers are explored, along with the possible combined effects on the overall performances.

The framework also represents a structured support for communication of improvement strategies both within the company and across its boundaries with the supply chain actors that are involved in the strategy.

Considering the companies interviewed with the purpose of validation as potential users of the developed tool, we appreciate the following interest:

- SEW expresses interest for the proposed approach and guidelines on non out-of-process activities and test modularization, possibly with the aim of increasing the number of tests that can be performed on semi-assembled products.
- GEA expresses interest for the proposed approach and guidelines on test modularization, possibly with the aim of extending the portion of standalone tests (currently just limited to mechanical verifications).
- SSS expresses interest for the proposed approach and guidelines on test procedures and out-of-test procedures and personnel responsibility due to the current lack of these aspects in the current process.

- TTT expresses interest for the proposed approach and guidelines on test modularization, possibly with the aim of increasing the number of tests that can be performed on standalone modules.
- Arol expresses interest for the proposed approach and guidelines on product modularization in order to enhance the possibility of performing a certain portion of the total tests on standalone modules. It also identifies of interest exploring interventions on the customer’s side in order to reduce the variability in the type of tests that it can be asked to perform depending on the customer.

Section 10: Conclusions & Future Research

10.1 Conclusions

A testing process in manufacturing (as it has been described in section 1.2) has been identified as the object of analysis for this Thesis Work.

Two Research Questions have been formulated with respect to the object of analysis:

1. “What descriptive variables can be identified in order to characterize a specific testing process?”

2. “What configurations can be proposed for the improvement of a specific testing process depending on different business characteristics?”

The study performed within this Master Thesis seems to have accomplished the research needs defined by the Questions.

A set of twelve variables for the characterization of a testing process have been defined on the base of the literature analysis (section 2) and three case studies (section 3,4 and 5).

The descriptive variables identified are, namely:

- Product modularization
- Independent test modules
- Test procedures structure
- Out-of-process activities
- Personnel responsibilities
- Testing setup
- Personnel scheduling
- Collateral testing activities
- Relationship with suppliers
- Number of suppliers per product
- Number and relevance of customers
- Stocks.

An assessment method has been proposed for each of the variables identified; this allowed, given a specific testing process, to define its characteristics by attributing a value to each descriptive variable.

This represented the preliminary step for the identification of a set of guidelines concerning configuration aspects of the testing process. The guidelines have been proposed on the base of each variable with the aim of improving the performances of the specific test process under assessment for that specific variable.

The identification of improvements for a testing process has been based on a set of specific KPIs deemed of relevance. The KPIs have been defined on the base of factors emerged as critical for a testing process, as exposed in section 1.4. The KPIs are, namely:

- Total Lead Time
- Internal Lead Time
- Cost of Testing
- Quality
- Overall Testing Process Efficiency.

The variables and their correspondent configuration guidelines have been structured in a framework. An application of it has been proposed on a real case with explanatory purpose (section 8).

The framework has been proposed to a set of five manufacturing companies with the aim of performing a validation campaign and identifying cues for tailoring the guidelines on the base of specific business characteristics (section 9).

The results of this validation campaign proved the utility of the tool for the purpose it has been intended for.

The identified variables have been acknowledged significance for the description of a testing process, even if to different extents. The bundle of variables related to product and tests modularization has been identified as the core one; the variables related to test procedures, out-of-process management, personnel responsibilities and those involving suppliers and customers have also been acknowledged a high relevance.

Concerning the business characteristics that could require tailoring the configuration guidelines proposed, five of them have been identified:

- Volume and variety
- Type of assembly performed internally

- Subsystem as a complex system
- Multiple modularity levels
- Complexity and number of modules interfaces.

The proposed configuration guidelines have then been tailored considering each of the business characteristic above listed.

With particular regards to the type of assembly performed internally, the validation showed a good applicability of the model also to those companies that partially violate the premise of outsourced manufacturing as defined at the very beginning of this analysis.

The final outcome of this Thesis Work is a framework whose purpose is to represent a handy tool for a manufacturing company which is considering the opportunity of improving the performances of its testing process. The tool is proposed in its graphical ready-to-use format in annex 6.

The following paragraph is dedicated to the exposition of those points that could be made object of future research, with the aim of improving or extending the validity of the proposed framework.

10.2 Future research

A few main points where to address future research are identified.

- Further validation campaigns could be carried out with the purpose of assessing the robustness and applicability of the model. A bigger and more diversified sample of companies could be selected for this purpose.

- Despite the validations have proven an overall validity of the identified variables, there is no evidence of their exhaustiveness with respect to the purpose of analysis. A possible future development could address the problem of identifying a set of variables which benefits of both significance and exhaustiveness by identifying additional variables to be integrated to the proposed set.

- The set of business characteristics on the base of which to tailor the configuration guidelines could be extended. This could be also achieved with further validation campaigns carried out on companies belonging to more diversified industries.

- The premise of outsourced manufacturing, as defined at the very beginning of this analysis, has been relaxed during the validation campaign by taking into account also manufacturing companies performing internal assembly. This has shown a possible extensibility of the model also for this type of companies, though the opportunities and limitations of doing so have been appraised just on the base of the few cases considered. A possible direction for future research could therefore be represented by an extensive analysis of this issue in order to get a more solid evidence of the model extendibility.

Annexes

Annex 1: Company visit 1 – Arol S.p.A.

The company produces and tests highly customized rotary and single-head capping machines.

The company produces according to an engineer-to-order (ETO) logic. Every job order signed by the sales managers has to be engineered first by the engineering department and then is launched in production.

The production steps are the same for all the different product families, though the single phases are customized depending on the type of product. The LT for a single machine spans from 40hrs until 400hrs. The company produces around 700 machines per year (roughly two machines per day outbound).

Due to the high customization of the product, a relevant proportion of the production activities is carried out in-house (nearly 90% of the production costs is accrued to the internal production). The other activities which are executed internally are assembly and testing.

In particular, each phase accounts for a specific percentage of the machine total LT, as follows:

- Engineering department: 40%
- Purchasing/Production department: 20%
- Pre-assembly and Assembly department: 10% and 20%, respectively
- Testing department: 10%

Despite the total time of permanence for a single machine in the testing department is only 1/10 of the overall LT, the testing activities are perceived as extremely critical for the company. According to Mr. Barbieri, this is due to two factors:

- The presence of customers located worldwide implies that the cost of machine testing before shipment outweighs the cost of possibly detecting errors on-site at the customer's.
- The company's final product might be only a part of the final customer's machine; this implies that in case an error is detected on-site at the customer's, the error-fixing campaign would be carried out on a complex machine where the company's product just represents a component. This brings along increased risks related to the on-site intervention and specific technical know-how needed for the personnel who execute the intervention.

Ranking of the current testing process conditions

1) Degree of product modularization: LOW.

   The final product is composed by subassemblies, though they cannot be considered as proper modules. Mr. Barbieri mentioned an ongoing initiative of product re-engineering oriented towards the definition of product modules; this initiative is nonetheless at a premature stage, so that it is yet not possible to appreciate its outcomes. The development of this initiative currently involves both the R&D department and the engineering department at multiple stages in order to define a modularization. This initiative is acknowledged as strategic for the company due to his market-driven nature: customers are indeed increasingly asking for higher product customization and shorter delivery times, and modularization has been identified as a correct response to this kind of requirements.

2) Degree of identification of independent functional modules: LOW.

   Despite the products are composed by subassemblies, it is not possible to consider those as functional modules. It is not possible indeed to test their interconnected functioning by means of specific tests that do not involve other parts. The whole system as it is has to be tested as a whole.

3) Degree of strategic suppliers' relevance: LOW.

   Arol's suppliers are classified as mostly traditional. Being most of the production executed in-house, Arol's suppliers mostly supply on-catalogue components, or components specifically engineered for the company; these last ones are said not require in any case a strategic relationship to be in place. Mr. Barbieri perceived this descriptive variable as not relevant with respect to his reality due to the high percentage of production which is executed in house.

4) Degree of procedure structuring: HIGH.

   The testing procedures are structured and standardized across the organization. A written codification of testing procedures is in place as well as systematic upgrades whenever a new testing procedure is added or a new type of error is detected. A weekly verification of the errors detected is held by the shopfloor manager in order to give the engineering and technical department a feedback on the shopfloor operating performances.

5) Degree of personnel responsibility: HIGH.

The testing operators are assigned the responsibility to solve problems on the machines undergoing testing whenever encountered. In case the testing operators are not able to solve the problem, the escalation process starts. The first hierarchical report is the engineering department which assesses whether the error that prevents the test to be executed correctly can be imputed to engineering. In case this condition is not verified, the second line report is the job order manager which internally decides the most suitable resource to be made responsible for the problem solving or, as a last resource, contacts the final customer in order to get to an agreement on the possibly delayed delivery date.

6) Presence of stocks in the testing process: NO.

No stocks are present in the testing area. Two machines are tested every day (on average), with no queues at the testing stage.

7) Presence of testing setup activities: YES.

The testing setup activities are of two types:

- Preparation of the client’s components (the specific cap and the vessel)
- Electrical and pneumatic wiring

The proposed guideline with regards to setup has been fully agreed upon by Mr. Barbieri. He agrees indeed that the time needed to execute this testing setup activities should be reduced and optimized by means of SMED and 5S activities. Such Lean tools have started to be implemented recently in the company, but their benefits have not yet been visible.

8) Presence of testing collateral activities: NO.

There are no collateral activities in the company’s testing process.

9) Personnel scheduling: CENTRALIZED.

The testing personnel scheduling is centralized under the responsibility of the shopfloor manager. Therefore the testing operators are scheduled according to the first machine available to undergo the testing activities, and they are allocated to the same machine up to correct complete execution of the whole procedure. Only at this point the testing personnel can be re-scheduled on a new machine.

10) Number of suppliers per product: NOT RELEVANT.

In this case this descriptive variable has not been considered as relevant for Arol due to production mostly carried out in-house and suppliers mostly providing standalone components or subassemblies. This descriptive variable has been indeed defined according to the definition of testing process as the Authors intended it (see literature overview), which is different from the modus operandi within the company.

11) Degree of customer relevance: HIGH for OEM and LOW for final customers.

Arol's customer can be clustered in two families:

- OEM, manufacturing products where Arol's machine represents a component.
- Final customers who purchase Arol's rotary or single-head capping machines.

Due to the different bargaining power of the two kinds of customers, Mr Barbieri backs the distinction proposed in the framework. In particular, an initiative is already ongoing for the definition of mutually agreed testing procedures with the OEM customers.

Perceived benefits deriving from the implementation of the guidelines

The assessment of the company with respect to the descriptive variables identified in the framework has resulted optimal for the following variables:

- Degree of procedure structuring
- Degree of personnel responsibility
- Presence of stocks in the testing process
- Presence of collateral activities
- Degree of personnel scheduling
- Degree of customer relevance with respect to the final customers.

On the other hand, Mr. Barbieri acknowledges the benefits of the guidelines proposed for those descriptive parameters which have been rated as not optimized. Arol is indeed already undertaking a product re-engineering initiative with the aim of defining and standardizing product modules. This would potentially bring along the possibility of manufacturing and testing individual modules rather than the product as a whole and to consequently shorten the LT of testing operations as explained in the framework.

Mr. Barbieri also agreed on the necessity of defining the testing procedures jointly with the customer. He stressed, though, that due to the characteristics of the business (with particular reference to increasing request for customized products) it might be difficult to have the upper hand over the customer with respect to his requests for variations or supplementary tests.

Assessment of the constraints on the adoption of proposed solutions

The constraints that would prevent the company to adapt to the best practices suggested by the framework are punctually defined on the individual parameters.

- As already mentioned, a constraint in defining either a product or test modularization is given by the need for complex and repeated interfaces with the R&D and engineering department, with the aim of tests or product re-engineering.
- Moreover, the guidelines proposed on the base of the assessment on the strategic importance of suppliers have been identified as not significant in the specific case, due to the predominant presence of inhouse production. The same consideration has been advanced with respect to the guidelines proposed on the base of the assessment on the number of suppliers per product, due the same reason exposed above.
- With regards to setup activities, no evident obstacle is identified apriori in the utilization of SMED and 5S methodologies. The utilization of these techniques has not been previously taken into account due to the fact that, despite the setup activity being identified as wasteful, its optimization has never been addressed in a systematic way.
- Concerning the high degree of customer relevance identified with respect to the OEM customers, Mr. Barbieri mentioned the increased pressure for higher product variety and decreased production Lead Time as the principal constraints to the applicability of the proposed guidelines. These bring along a major difficulty on having the upper hand over the customer concerning the agreement of a fixed set of procedures, even though Mr. Barbieri acknowledges this practice would have a positive impact on the process performances.

Exhaustiveness of the model and further comments

An overall positive feedback has been given with regards to the exhaustiveness of the model. The most significant descriptive variables for the description of a testing process appear to have been covered within the assessment. The proposed guidelines are considered as coherent with the criticalities identified, and oriented towards a process optimization.

Some specific variables are identified as not relevant for the company, mostly due to the fact that the framework has been conceived having as a target a testing process with some distinctive characteristics, as defined in the incipit of this thesis work. The testing process as carried out in Arol partially violates these defined characteristics, being most of the manufacturing performed inhouse rather than outsourced.

As a further comment, Mr. Barbieri suggests an additional element of interest for the process guidelines. This concerns considering whether the customer should be involved in the definition of the testing procedures, in what phase of the product lifecycle this should happen and to what extent. His position regarding this aspect supports the involvement of the customer in the definition of the testing procedures early in the design stage, being production very customized in this specific case.

Annex 2: Company visit 2 – TTT S.p.A.

The company produces and tests highly customized complete lines for beverages packaging in plastic or glass containers. In particular, the product variety derives from three different dimensions:

- Size – which defines the productive capacity of the final machine line.
- Accessories – add-ons for the machine line.
- Applications – which depend on the type of bottling or packaging.

The machine LT varies a lot depending on the model.

In particular, each phase accounts for a specific percentage of the total LT of a complete line according to the following classification:

- Engineering department: 30%
- Production department: 40%
- Assembling department: 20%
- Testing department: 10%.

When an order is received, the engineering department is in charge of the engineering part for both modules manufactured externally and mechanical parts which are produced internally. The subsequent phases are manufacturing and the final assembly which integrates predefined machines modules and machine parts.

Ranking of the current testing process conditions

1) Degree of product modularization: HIGH.

In fact the product is composed by complex subassemblies which can be considered as physical modules.

2) Degree of identification of independent functional modules: MEDIUM-LOW.

The operation manager at TTT S.p.A. confirmed that tests can be performed to a greater or lesser extent on the individual modules depending on the specific module or machine part and its characteristics. Discrimination can be made depending on the module/machine part type:

- Certain kinds of modules/machine parts can be tested 100% in a standalone fashion;
- Certain kinds of modules/machine parts can be tested to a lesser extent as individual modules/machine parts since there is presence of mechanical, electrical and flow interfaces; no simulator has been developed yet in order to overcome this restriction.

TTT S.p.A. therefore performs tests on individual modules/machine parts whenever possible, according to the above mentioned constraints. Testing activities are scheduled in such a way that guarantees the parallelization of modules testing carried out at the supplier's site and machine parts testing carried out inhouse. This testing logic requires, as a consequence, a system integration test in order to guarantee the interoperability and the correct functioning of those modules/machine parts which have not been completely tested. This integration test is currently carried out directly at the customer's site due to the cumbersome dimension of the final machine; the dimensions prevent the possibility of assembling all the modules and machine parts within the company in order to perform the system integration test before the final shipment takes place.

3) Degree of strategic suppliers' relevance: HIGH.

The suppliers of machine modules are strategically relevant for the company due to the presence of high switching costs. The company works with these suppliers through framework agreements; production plans are also mutually shared in order to enable a synchronized shipment to the final customer of all the modules composing a machine line.

4) Degree of procedure structuring: HIGH.

The testing procedures are structured and standardized across the organization. A written codification of testing procedures is in place as well as systematic upgrades whenever a new testing procedure is added or a new type of error is detected. The testing procedures are shared on a common folder which is accessible to every employee in the organization.

5) Degree of personnel responsibility: HIGH.

The testing personnel are specialized electrical or mechanical operators. The testing operators are assigned the responsibility to solve problems on the machines undergoing testing whenever encountered. Also in this case, whenever the testing operators are not able to solve the problem, the escalation process starts. The first hierarchical report is their direct supervisor who is generally more expert. If also the supervisor is not able to solve the problem, the second line report is the production manager who analyzes the root causes of the error detected and has the right to determine which action needs to be undertaken. As a last resort, a communication is given to the client that the company is unable to meet the predefined delivery date.

6) Presence of stocks in the testing process: NO.

No stocks are present in the testing area, though some more generic items are kept on stock in the warehouse. These items are:

- Consumption material for testing.
- Materials with a high rotation index managed in a re-order point logic.
- Materials which are deemed relevant for the after sales service and therefore are kept as a safety stock.

7) Presence of testing setup activities: YES.

The testing setup activities are of three types:

- Modules/machine parts positioning.
- Preparation of tools and equipment for the testing activities.
- Wiring the PLCs to the machine line.

The proposed guideline with regards to setup has been fully agreed upon by Mr. A.R. SMED and 5S initiatives have not been implemented yet due to the fact that the company is a recent acquisition of a holding and some parts of the manufacturing process are still in need to undergo optimization campaigns or complete re-engineering.

8) Presence of testing collateral activities: NO.

There are no activities that can be identified as collateral within the company's testing process.

9) Personnel scheduling: CENTRALIZED.

The testing personnel scheduling is centralized under the responsibility of the production manager. As in Arol's case, the testing operators are scheduled according to the first machine available to undergo the testing activities, and they are allocated to the same machine up to correct complete execution of the whole procedure. Only at this point the testing personnel can be re-scheduled on a new machine.

10) Number of suppliers per product: MULTIPLE.

TTT S.p.A. keeps different suppliers per product. The number of suppliers per machine line generally depends on the number of modules composing the machine itself. Moreover, there are multiple suppliers (at least two) per each module type. Different suppliers for the same module are chosen according to several reasons:

- Customer request to use a specific supplier which it has certified.
- Supplier's production capacity.
- More strategic reasons such as prices competitiveness.

11) Degree of customer relevance: HIGH for big multinationals and LOW for smaller customers

TTT S.p.A.'s customer can be categorized in two families:

- Multinational customers, characterized by a high bargaining power.
- Smaller customers, characterized by a lesser bargaining power compared to multinationals.

Perceived benefits deriving from the implementation of the guidelines

The assessment of the company with respect to the descriptive variables identified in the framework has resulted optimal for the following variables:

- Degree of product modularization
- Degree of strategic supplier' relevance
- Degree of procedure structuring
- Degree of personnel responsibility
- Presence of stocks in the testing process
- Presence of collateral activities
- Degree of personnel scheduling
- Degree of customer relevance with respect to the final customers.

On the other hand, Mr. A.R. acknowledges the benefits of the guidelines proposed for those descriptive parameters which have been classified as not optimized.

A significant benefit is identified in the possibility of carrying out standalone tests on individual modules or machine parts. The company has indeed already planned to develop a series of equipment that would enable a more comprehensive test on those modules that still do not allow standalone testing.

As a second point, Mr. A.R. highlights an interest in investigating which activities within the company could be identified as collateral to testing.

Also concerning the presence of setup activities, it has been acknowledged a benefit in the adoption of the 5S and SMED in order to reduce the impact of the inefficiencies on the overall process.

As a final note, the descriptive variable "number of suppliers per product" has been acknowledged as not particularly relevant for the company under analysis. The choice of keeping a single module supplier in a market characterized by a high demand variety would generate rigidity and loss of competitiveness; this generates a loss of validity for the guideline proposed in that case.

Assessment of the constraints on the adoption of proposed solutions

The constraints that would prevent the company to adapt to the best practices suggested by the framework are punctually defined on the individual parameters.

- Concerning the presence of setup activities, no evident constraints have emerged with regards to the possible implementation SMED and 5S; indeed the major reason why these kinds of initiatives have not been undertaken yet has to be referred to the recent acquisition of the company.
- A major constraint is identified in the development of equipment that would enable standalone tests. The massive involvement of technical and R&D department makes this guideline particularly cumbersome in terms of re-engineering effort; nonetheless, due to the acknowledged benefits, this initiative is currently ongoing within the company.

Exhaustiveness of the model and further comments

Mr. A.R.'s comment about the degree of exhaustivness of the model has been rather positive. In particular Mr. A.R. akwnoledged a value for both the decriptive variables identified and their proposed guidlines.

The specific variable "number of suppliers per product" is identified as not relevant for the company because of the competitivity conditions of a market characterized by a highly customized demand, where keeping multiple suppliers per type of module is considered as a strategic choice.

Annex 3: Company visit 3 – SEW EURODRIVE Ltd.

The company, part of the German group SEW EURODRIVE, produces and tests highly customized electrical gearmotors and reducers for a variety of industrial customers.

The plant located in Solaro (MI) is the only assembly site for Italy. The volumes of production are around 250 gearmotors per day. The assembly site is fully organized on the base of Lean Manufacturing principles; particularly, an organization in cells is kept for those products with higher volumes and a more standardized demand, while job shops are kept for those products with lower demand volumes and higher customization.

Every product undergoes testing in between the assembly and paining phase. The tests, whose duration does not exceed few minutes in case no error is detected, aims at ensuring that the main quality features are present in the product. The main standard features normally tested in a gearmotor product type are the electrical absorption, the electrical insulation, the number of spins per minute and the level of noise.

Ranking of the current testing process conditions

1) Degree of product modularization: LOW.

   The product architecture for a gearmotor product type is rather simple: it is possible to identify only two layers, where one is the finite assembled product and the one immediately below is the components layer. A possible intermediate layer could be identified, composed by some small simple subassemblies. Nonetheless, the subassemblies are in turn rather simple and therefore no explicit functionality can be attributed them, so that it would be incorrect defining them as modules.

2) Degree of identification of independent test modules: LOW.

   The whole gearmotor is testes as a whole once the assembly phase is terminated

3) Degree of strategic suppliers' relevance: NOT RELEVANT.

   The main supplier for the company is the German mother company. Most of the components assembled within a product are supplied directly by the mother company, which therefore plays in this case the part of the "dummy supplier". The condition is acknowledged as out-of-the market since the performances in terms of Lead Times and punctuality guaranteed by the mother company could not be realistically achieved with any other supplier in the competitive market.

4) Degree of procedure structuring: MEDIUM.

   The testing procedures are codified and made available for the test operator, while concerning the out-of-process activities no structured procedure is in place.

5) Degree of out-of-process structuring: LOW.

   No structured procedure is in place for error resolution. The usual practice in the company is proceeding with escalation within the shopfloor whenever the test operator who has detected an error during testing is not able to solve the issue.

6) Degree of personnel responsibility: HIGH.

   The personnel in charge of performing tests on the assembled products are specifically trained figures. It was common practice in the company to allocate tests activities to assembly personnel as a form of job rotation. In the past few years, though, the personnel performing test is a specialist figure dedicated full time to this activities. This has been acknowledged as a form of better quality guarantee.

7) Presence of stocks in the testing process: YES.

   Stocks of several parts are present in the testing area, mostly for assembly purposes and not directly in relation with test activity.

8) Presence of testing setup activities: YES.

   The test phase implies the electrical powering of the single item undergoing tests. The activity is rather simple and does not account for a significant portion of the total Test Lead Time.

9) Presence of testing collateral activities: NO.

   There are no collateral activities in the company's testing process.

10) Personnel scheduling: CENTRALIZED.

    The testing personnel scheduling is centralized under the responsibility of the shopfloor manager.

11) Number of suppliers per product: SINGLE.

    Despite some third part suppliers are present, supplies are mostly prerogative of the mother company. In any case, this case this descriptive variable has not been considered as relevant for SEW EUDRIVE due to production mostly carried out in-house and supplies being mostly composed by individual mechanical or electrical components.

12) Degree of customer relevance: HIGH and LOW

    The pool of customers served by the company spans significantly from local small and edium enterprises to big multinational companies.

Assessment of the constraints on the adoption of proposed solutions

The constraints that would prevent the company to adapt to the best practices suggested by the framework are punctually defined on the individual parameters.

- The major constraint in this case for the definition of standalone tests on individual module is given by the presence of simple components or subassemblies at the architectural level immediately below the product one.

  There is indeed a lack of significance for tests to be carried out on the individual subassemblies, besides a tolerance inspection, due to the fact that the functionalities of interest to be tested for each single subassembly emerge only in a context of complete product assembly.

- Another constraint is given by the presence of the mother company as a mostly exclusive supplier; this makes the variables related to supply chain and supplier relevance lose in significance.

Exhaustiveness of the model and further comments

An overall positive feedback has been given with regards to the exhaustiveness of the model, the significance of the variables and the guidelines proposed accordingly.

The variables identified with regards to the relationship with suppliers have been identified as of less relevance due to the fact that there is presence within this case of an internal manufacturing activity which was excluded by the initial formulation of testing process definition. Furthermore, the presence of an “internal” supplier constitutes a limit to the applicability of the guidelines proposed.

Moreover, the interviewee points out as a point of interest the guideline suggesting structured management of out-of-process activities, which is currently not present in the company.

Concerning modularization, the interviewee points out that the creation of modules in a context where high customization is present would bring along an undesired level of rigidity in the system. If the company was operating on a product catalog base, as most of the competitors do, the company would be interested in exploring opportunities for modularization in order to leverage the possible benefits both from a production and a testing standpoint.

Annex 4: Company visit 4 – SSS S.p.A.

The company produces and tests highly customized filling machines. These machines are part of a final product, which is a filling line composed of different machines whose input is bulk beverage and whose output is filled bottles packaged onto standard pallets. With regards to the following assessment, we are going to consider the single filling machine as the object of analysis.

The company produces according to an engineer-to-order (ETO) logic. As for the volumes, the company produces about twenty machines per year.

The company's products are highly customized and the degree of customization is defined on more levels (shape of the bottle, type of cap and setting of the piping system depending on the type of liquid to be filled in the bottle). These machines are composed by both hardware and software parts.

The production steps are the same for all the different product families, though the single phases are customized depending on the type of product. The LT for a single machine spans from 6 days until 14 days.

Ranking of the current testing process conditions

1) Degree of product modularization: HIGH.

   In fact the product (the filling machine) is composed by complex subassemblies which can be considered as physical modules.

   In particular, in the filling machine there are five subassemblies (two for the sterilization, one for rinsing, one for filling and one for sterilizing the cap).

2) Degree of identification of independent test modules: LOW.

   Despite physical modules are identified, this peculiarity is not leveraged. The whole product is indeed tested as a whole, and no tests on standalone modules are performed.

3) Degree of strategic suppliers' relevance: HIGH.

   With regards to the filling line, SSS S.p.A.'s suppliers are classified as mostly collaborative. In fact their assembling plans are scheduled accordingly to the SSS S.p.A. ones since the final product (the bottling line) is assembled at the final customer's site and all the modules have to be prepared and shipped accordingly in order to arrive at destination at the same time. Moreover, due to the fact that the final product (bottling line) is made up of several modules, each one of them engineered and assembled at a different supplier, the relationship among them is collaborative.

With regards to the single filling machine, the relevance of suppliers becomes lower. The suppliers indeed in this case provide the company mostly with standalone components or subassemblies, rather then complex modules or machines.

4) Degree of procedure structuring: MEDIUM.

The testing procedures are structured and standardized across the organization. On the other hand, a written codification of testing procedures lacks.

5) Degree of out-of-process structuring: LOW.

No structured procedure is in place for error resolution. The usual practice in the company is proceeding with escalation within the shopfloor whenever the test operator who has detected an error during testing is not able to solve the issue.

6) Degree of personnel responsibility: HIGH.

The testing operators are assigned the responsibility to solve problems on the machines undergoing testing whenever detected. In case a problem which cannot be solved by the operator emerges, the shop floor manager is informed and he is given the responsibility and authority to take a decision on the work.

7) Presence of stocks in the testing process: YES.

Stocks of several parts are present in the testing area, mostly for assembly purposes and not directly in relation with test activity.

8) Presence of testing setup activities: YES.

The testing setup activities are of two types:

- Preparation of the tools and equipment needed to perform the tests
- Electrical and pneumatic wiring

9) Presence of testing collateral activities: NO.

There are no collateral activities in the company's testing process.

10) Personnel scheduling: CENTRALIZED.

The testing personnel scheduling is centralized under the responsibility of the shopfloor manager.

11) Number of suppliers per product: MULTIPLE.

In this case this descriptive variable has not been considered as relevant for SSS S.p.A. due to production mostly carried out in-house and suppliers mostly providing individual components or subassemblies.

12) Degree of customer relevance: HIGH

SSS S.p.A. customers are the big multinational companies of the beverage industry. Despite some actions have been undertaken in order to define the testing procedures with the customers, most of the time the customer itself due to its multinational organization has different requirements depending on their regional offices. Therefore, Mr. G.N. told us that due to the high customization and differentiation depending on the market in which the filling machines will be sold, a relevant percentage of the testing procedure have to be considered as highly customized on the specific machine.

Assessment of the constraints on the adoption of proposed solutions

The constraints that would prevent the company to adapt to the best practices suggested by the framework are punctually defined on the individual parameters.

- The major constraint in this case for the definition of standalone tests on individual module is given by the necessity of operating tests without the other utilities present in the end filling line and in absence of the actual liquid that would be used by the customer. According to the interviewee, this limits the number of tests that can be performed both on the individual filling machine and on its composing modules as well.
- Another constraint is given by the presence of a multinational customer with relevant bargaining power and significantly different needs in terms of product performance depending on the regional areas where the line is going to be installed. This limits the possibilities of framing test procedures into a standard agreement that could be applied to every product sold to the same customer.

Exhaustiveness of the model and further comments

Mr. G.N. commmented on the significance of the descriptive variables analyzed in the framework as well as their exhanustivness with respect to the description of a generic testing process. The proposed guidelines are considered as coherent with the criticalities identified, and oriented towards a process optimization.

The variables identified with regards to the relationship with suppliers have been identified as of less relevance due to the fact that there is presence within this case of an internal manufacturing activity which was excluded by the initial formulation of testing process definition.

Furthermore, the interviewee points out as a critical point the achievement of the proposed solution of implementing simulation tools in order to extend the portion of tests that could be carried out as standalone tests on individual modules. A possible simulation tool needed in this case would be a bottle feeder for the filling machine to operate in the same conditions as at the customer's site. This has been identified as inconvenient both from a space occupation and an investment point of view. The reason of this inconvenience has been traced back to the low production volumes that would make the investment anti economic compared to the benefits that would arise.

Annex 5: Company visit 5 –GEA Procomac S.p.A.

The company produces and tests highly customized aseptic filling machines. These machines are part of a final product, which is a filling line composed of different machines whose input is bulk beverage and whose output is filled bottles packaged onto standard pallets. With regards to the following assessment, we are going to consider the single filling machine as the object of analysis.

The company produces according to an engineer-to-order (ETO) logic. As for the volumes, the company produces tens of machines per year.

The company's products are highly customized and the degree of customization is defined on more levels (shape of the bottle, type of cap and setting of the piping system depending on the type of liquid to be filled in the bottle). These machines are composed by both hardware and software parts.

Ranking of the current testing process conditions

1) Degree of product modularization: HIGH.

   In fact the product (the filling machine) is composed by complex subassemblies which can be considered as physical modules.

   In particular, in the filling machine there are five subassemblies (two for the sterilization, one for rinsing, one for filling and one for sterilizing the cap).

2) Degree of identification of independent functional modules: MEDIUM/LOW.

   The aseptic filling machine is currently tested for 80% of its cycles, due to the absence of the other line utilities and the actual liquid that would be used by the customer. Given this as a premise, the identified subassemblies within the filling machine are partially tested as standalone modules. Standalone tests account for just around 20% of the total tests and are just composed by mechanical tests. The remaining 80% (64% of total tests on the machine considered as part of the line) of tests is performed on the fully assembled machine as a whole. In case of particularly stringent time constraints, only the software is tested in a standalone fashion, therefore accounting for 40% of the tests that are performed on the filling machine (32% of tests on the machine considered as part of the line).

3) Degree of strategic suppliers' relevance: HIGH.

With regards to the filling line, GEA Procomac S.p.A.'s suppliers are classified as mostly collaborative. In fact their assembling plans are scheduled accordingly to the company's ones since the final product (the bottling line) is assembled at the final customer's site and all the modules have to be prepared and shipped accordingly in order to arrive at destination at the same time. Moreover, due to the fact that the final product (bottling line) is made up of several modules, each one of them engineered and assembled by different suppliers, the relationship among them is collaborative. Recently, the company has adopted a strategy of vertical integration aimed at internalizing the production of those line modules that have been deemed strategic for penetrating new markets.

With regards to the single filling machine, the relevance of suppliers becomes lower. The suppliers indeed in this case provide the company mostly with standalone components or subassemblies, rather then complex modules or machines.

4) Degree of procedure structuring: HIGH.

The testing procedures are structured and standardized across the organization. A written codification of testing procedures is in place. On the other hand, GEA Procomac S.p.A. does not have in place a structured system for the systematic upgrade whenever a new testing procedure is added or a new type of error is detected and one wants to keep track of the identified solving procedure.

5) Degree of out-of-procedure structuring: LOW.

No structured procedure is in place for error resolution. The usual practice in the company is proceeding with escalation within the shopfloor whenever the test operator who has detected an error during testing is not able to solve the issue.

6) Degree of personnel responsibility: HIGH.

The testing personnel are six people in total: specialized electrical (four) and mechanical (two) operators. The testing operators are assigned the responsibility to solve problems on the machines undergoing testing whenever encountered. Whenever the testing operators are not able to solve the problem the escalation process starts. The testing operators respond directly to the quality manager (Mr. Ferrarini).

7) Presence of stocks in the testing process: NO.

There is presence of stocks related to assembly activity; nonetheless they are managed in an optimized fashion with a kanban system.

8) Presence of testing setup activities: YES.

The testing setup activities are of two types:

- Preparation of the tools and equipment needed to perform the tests.
- Electrical and pneumatic wiring.

9) Presence of testing collateral activities: NO.

There are no collateral activities in the company's testing process.

10) Personnel scheduling: CENTRALIZED.

The testing personnel scheduling is centralized under the responsibility of the quality manager.

11) Number of suppliers per product: MULTIPLE.

In this case this descriptive variable has not been considered as relevant for GEA Procomac S.p.A. due to production mostly carried out in-house and suppliers mostly providing individual components or subassemblies.

12) Degree of customer relevance: HIGH

GEA Procomac S.p.A. customers are the big multinational companies of the beverage industry. Despite some actions have been undertaken in order to define the testing procedures with the customers, most of the time the customer itself due to its multinational organization has different requirements depending on their regional offices. Therefore, Mr. Ferrarini told us that due to the high customization and differentiation depending on the market in which the filling machines will be sold, about 20% of the testing procedure have to be considered as highly customized on the specific machine.

Assessment of the constraints on the adoption of proposed solutions

The constraints that would prevent the company to adapt to the best practices suggested by the framework are punctually defined on the individual parameters.

- As in the case of SSS S.p.A., the major constraint in this case for the definition of standalone tests on individual module is given by the necessity of operating tests without the other utilities present in the end filling line and in absence of the actual liquid that would be used by the customer. According to the interviewee, this limits the number of tests that can be performed both on the individual filling machine and on its composing modules as well.

- Another constraint is given by the presence of a multinational customer with relevant bargaining power and significantly different needs in terms of product performance depending on the regional areas where the line is going to be installed. A few attempts have already been made in order to agree a standard catalogue for individual customers; this would have implicated more standardized features for the products ordered by the same customer and consequently more standardized tests to be performed on the individual machines. Nonetheless, so far the outcome of the initiative has not been successful due to continuous requests for further customizations of products on the agreed catalogues.

Exhaustiveness of the model and further comments

The framework has been generally defined as representing to a great extent the main features, variables and guidlines characterizing a testing process and aimed at optimizing it.

The variables identified with regards to the relationship with suppliers have been identified as of less relevance due to the fact that there is presence within this case of an internal manufacturing activity which was excluded by the initial formulation of testing process definition.

As in the case of SSS S.p.A., the guideline regarding the development of simulation tools could be possibly anti economical due to the fact that the low production volumes and the high product variety would make an investment in simulation tools not offset by the benefits.

As a further comment, Mr. Ferrarini suggests that a practice currently in place in the company could be of interest within the framework guidelines.

The company currently implements the practice of establishing a temporary pool of experts for the definition of customized test procedures depending on the type of product that needs to undergo testing. The definition of these procedures includes creating a list by picking from a standard pool of tests available; this is done downstream of a risk assessment on the specific product, so that each and only necessary test is included in the list. The list is then prioritized, ranking first those tests aimed at ensuring those functionalities that bring along the highest component of risk for the product.

Annex 6: Framework graphical representation

<table>
<tr><th>DESCRIPTIVE VARIABLE</th><th colspan="4">GUIDELINE</th><th colspan="4">GUIDELINE NOTES</th></tr>
<tr><td>1) Degree of product modularization</td><td colspan="2">HIGH</td><td colspan="2">LOW</td><td colspan="2">Delegation of tests on individual modules to the module manufacturer, if any, enabling parallelization and externalization of individual modules tests</td><td colspan="2">R&D department should be involved</td></tr>
<tr><td>2) Degree of identification of independent functional modules [2]</td><td>HIGH</td><td>M-H</td><td>M-L</td><td>LOW</td><td>In the AS IS situation, tests can be done 100% as individual tests on functional modules

This situation is ideal.</td><td>In the AS IS situation,
1.Tests on individual modules that can be parallelized using a simulator to simulate the interface with other functional modules
2. “system tests” on the whole system [3]
The guideline is points at the situation corresponding to the HIGH level. R&D department might be involved</td><td>In the AS IS situation,
1. Tests on individual modules that can be parallelized
2. “System tests” on the whole system

The guideline points at the situation corresponding to the highest achievable among M-H or HIGH levels. R&D department might be involved</td><td>In the AS IS situation,
Tests have to be carried out 100% as a “system tests”

The guideline points at the situation corresponding to the highest achievable among M-L, M-H or HIGH levels. R&D department might be involved</td></tr>
<tr><td>3) Degree of strategic suppliers’ relevance</td><td colspan="2">HIGH</td><td colspan="2">LOW</td><td colspan="2">• Set framework agreements with suppliers
• Adaptation to takt must be asked to supplier when a takt exists
• Modules suppliers should be delegated the modules tests when individual tests can be performed on modules</td><td colspan="2">Set fixed agreements regarding quality penalties and introduce quality audits.</td></tr>
<tr><td>4) Degree of process structuring</td><td colspan="2">HIGH</td><td colspan="2">LOW</td><td colspan="2">No need for intervention</td><td colspan="2">Codification through written procedures must be achieved</td></tr>
<tr><td>5) Degree of out-of-error</td><td colspan="2">HIGH</td><td colspan="2">LOW</td><td colspan="2">Codification through written procedures must be achieved</td><td colspan="2">A preliminary assessment has to be carried out considering two parameters:
• Order of magnitude of number of causes that can be possibly</td></tr>
</table>

[2] specific parts of the product whose interconnected functioning is assessed by specific tests that do not involve other parts but the ones defined as functional module

[3] In this case tests carried out on individual modules are a higher proportion of total tests compared to the M-L solution, due to the usage of a simulator

activity structuring				determining each type of error encountered during testing[4] • Number of different people that are possibly involved in the resolution of each type of error [5]
6) Degree of personnel responsibility	HIGH	LOW	No need for intervention	A system of responsibilities attribution should be implemented, for instance with the creation of a "test owner" figure in order to improve quality outputs and motivation.
7) Presence of stocks in the testing process	NO	YES	No need for intervention	Modules or system shipments should be synchronized with the start of testing activities[6]
8) Presence of testing setup activities	NO	YES	No need for intervention	The testing setup (for instance mechanical and electrical wiring, product positioning, etc) should be reduced and optimized by the means of standard Lean tools such as SMED and 5S.
9) Presence of testing collateral activity	NO	YES	No need for intervention	Collateral activities should be linked in the process with the core testing activities through a pull flow and a single scheduling point.
10) Personnel scheduling	Centralized	De-centralized	No need for intervention	Centralize the testing and collateral activities personnel scheduling so to guarantee visibility and efficiency in the allocation of resources
11) Number of suppliers per product	Single	Multiple	No synchronization of pickings is needed [7]	A centralized milk-run picking from the suppliers is suggested in order to eliminate stock and synchronize activities
12) Degree of customer relevance	LOW	HIGH	A predefined set of standard testing procedures should be proposed	A collaborative strategy for testing procedure definitions should be adopted. It is important to reach agreements so that once the procedures have been mutually agreed, no extra-tests can be asked by the customer

LEGEND:

M-L = medium low

M-H= medium high

[4] It determines the need for a centralized information sharing about resolution methods, for instance a library of best practices

[5] It determines the need for an integrated progress-monitoring system that allows specialist personnel to plan specific interventions when needed

[6] If the company has bargaining power enough to guarantee convenient supplying deals to their suppliers, the intervention should be limited to the intermediation through a framework agreement and not to the direct managing of supplies

[7] In this case the parallelization of tests on modules can be just given through the utilization of more resources working in parallel.

GUIDELINE TO THE FRAMWEORK USAGE

This framework is thought to give operations mangers, industry experts and consultants a guideline on how to optimize a testing process. In this section some instructions on how to assess a manufacturing company's testing process are provided. The framework user has to assess the current situation of its testing process by choosing an option in the field "guideline" for every "descriptive variable" presented in the framework. After having selected the current situation for each testing process variable some conclusions can be drawn:

- **If all the chosen boxes are on the left hand side the company testing process is optimized to a great extent on the identified variables**
- **If all the chosen boxes are on the right hand side the company testing process is not optimized on the identified variables and some corrective actions have to be undertaken. An evidence of these corrective actions is proposed in the framework itself under the header "guideline notes"**
- **If a not linear pattern that connects all the chosen boxes has emerged, then the testing process needs some local improvement. In particular,**
  - **The testing process can be considered optimized for all those descriptive variables whose check is on the left hand side of the field "guideline"**
  - **The testing process can be considered not optimal for all those descriptive variables whose check is on the right hand side of the field "guideline". Specific corrective actions are found under the header "guideline notes".**

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