ICED13
INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

SUPPORTING THE MODIFICATION PROCESS OF PRODUCTS THROUGH A CHANGE MANAGEMENT TOOL

Marco MALATESTA (1), Roberto RAFFAELI (2), Maura MENGONI (1), Michele GERMANI (1)
1: Università Politecnica delle Marche, Italy; 2: Università Telematica eCampus, Italy

ABSTRACT
Updating products requires design activities, virtual and physical prototyping of new solutions, test and validation steps. If problems are detected at any of these stages, they cause iterations, waste of time and resources.
A change propagation method is initially described as a way to facilitate the introduction of product changes. The approach relies on a multilevel product representation, the modelling of the component dependencies, algorithms to compute the propagation of some desired changes. Outputs are represented by the list of the affected components and indices indicating the impact on the product requirements.
The method has been applied in the whole redesign process of a standard product like the fridge. Modifications must be usually released under time constraints. In this context, the outputs of the proposed method are an useful support to reduce iterations and resources waste. The experimentation has been based on case studies assigned to two groups of designers working with and without the tool.
It has resulted that designers become more aware of the implications of the engineering changes, they are allowed of better decisions and the whole process becomes shorter.

Keywords: change management, design methods

Contact:
Dr. Ing. Marco Malatesta
Università Politecnica delle Marche
Department of Industrial Engineering and Mathematical Sciences
Ancona
60131
Italy
m.malatesta@univpm.it

1 INTRODUCTION

The increasing need to offer in short time an even more variety of products and to meet the heterogeneous needs of customers have pushed manufacturing firms to update continuously designs of products and relative production systems. The key aspect is to introduce in products new functionalities and features in order to meet the rapid changes of the current dynamic environment. Aiming to this objective, it is clear that high efforts are required in design activities, in virtual and physical prototyping of news solutions and in test and validation phases of updated products. In fact, new functionalities of product must be thought, designed and validated thanks to software systems and physical mock-ups before they were put into the production systems. It means that shortcomings and problems detected at any of these stages cause iterations and waste of time. Therefore, new approaches are needed to maintain low associated costs and to manage development processes in a more straightforward way. Iterations should be minimized in order to save time, resources and then money.

This paper proposes a Change Propagation Method (CPM) to face this issue. CPMs allow to estimate the potential changes into the product that are required by the introduction or by the modification of some features. Usually, CPMs rely on modelling the dependencies of a component in order to compute the propagation of the introduced engineering change thanks to dedicated algorithms. If consequences of a change in design of parts of products, performances and production systems can be estimated in the early phases, the modification can be target of more viable solutions. This makes the whole process more efficient, faster and cheaper.

This paper is arranged as follows. Section 2 contains a review about change propagation approaches and their potential in the usage in the whole product development process. Then, Section 3 proposes a dependency-based change propagation approach to optimize the product development cycle. Section 4 describes a real process of industrial revision and reports some test cases to validate the usage of a supporting tool of change management. The main aim is to show the benefits obtained by the application of the tool in terms of cost and time savings. Conclusion and future works are finally discussed.

2 BACKGROUND

The main objective of a company is to gain a competitive edge in the market in which it operates. So it is necessary to manage the changes at any stage of the product life cycle. Growing interest in flexibility and efficiency of the industrial processes has led to expand researches and industrial applications in Engineering Change (EC). ECs are traditionally seen as a series of changes that impact various components of the product after it had gone into production (Wright, 1997). In recent years, EC concept has evolved to recognize the need to explore the effects of changes in products before they will be launched into production. The implementation of an EC requires a decision phase followed by activities of design and prototyping until the version of the new product will be approved and launched into production. In this context, the scientific world and the companies are making a step towards the implementation of the agile manufacturing of prototypes, whose strength lies in the ability to change quickly and easily (Huang and Mak, 1998).

Changes, especially on existing products rather than new, are ever more frequent and companies need to adapt their business to the rapid evolution of the market. In this view, ECs represent an important source of innovation. EC and its propagation could be assessed at various stages of the design process, but their estimate should be conducted as soon as possible to reduce costs that will inevitably increase at the end of the design process (Koh et al., 2012). The propagation of an EC is defined in Brooks and Mocko (2011) “as a progression where a change to one component or element of a system brings about sequential changes to one or more additional components or elements in the system”.

Understanding the nature of the change propagation is necessarily linked to the nature of the connections between components of a product. In literature exist examples and discussions about these linkages. Some of these are focused on the physical domain, such as linkages between components forming the product architecture, others on the functional domain, i.e. function-form relationships. Few researches are based on the interconnection between the two aspects. For instance, Kocar and Akgunduz (2010) have developed a probabilistic analysis of propagations by observing the implicit linkage between components. Cheng and Chu (2012) explain the EC propagation through a network of physical components and their related coupling strengths. On the other side, authors like Fei et al. (2011) have understood the relevance of functional analysis to assess the change propagation, they

have elaborated a method to assess the change propagation in design phase through both functional and structural architecture. Functions connect physical requirements of a product to the needs of the designer allowing the representation of a product to be abstracted in terms of definitions of simple functions and flows of material, energy and signal. The method involves the use of a composite matrix that clarifies the relationship between functional requirements and physical components of the same product. Some approaches have proposed to use dependencies between components and/or functions to compute the propagation in the product of a required EC. Engineering Change Management (ECM) systems have been proposed by Ahmad et al. (2012) as a contribute in the modelling of a EC and its propagation during the design and the development of a complex product. Kilpinen et al. (2009) has applied a method to assess the consequences of ECs in aerospace industry. Finally, Germani et. al. (2009) and Raffaeli et al. (2010) have proposed an extended multilevel representation framework to model complex dependencies among components, component attributes and implemented functions and to facilitate the modular representation of a product. The approach grounds on graph based algorithm to traverse the network of dependencies and compute impact indices on several product requirements and life cycle aspects.
The majority of the reviewed approaches focus on a specific aspect of the design process, mostly the structure of products in terms of components list. Although proved to be beneficial, such approaches have not clearly demonstrated the consequences of their usage on the whole design process, from the early evaluations of different design alternatives to the implementation of a specific one, until the realization of virtual and physical mock-ups and their experimentation. This paper seeks to describe the application of a CPM in design departments exploring consequences and benefits of the implementation of a certain EC at different steps, from its definition to the production phase.

3 METHOD

The multilevel framework to represent products in terms of functions, modules and architectures has been already described in previous works (Germani et al., 2009, Raffaeli et al., 2010). It has been chosen for evaluating and comparing different technical solutions and selecting the most effective one, estimating the necessary redesign activity. This approach and the related software tool, namely *Modulor*, will be here briefly recalled.

3.1 A change propagation approach based on dependency modelling

The prediction of the impacts of changes and their calculation are based on three different domains that represent a product: the functional structure, the modular structure and the product architecture. The first is a functional representation, where for function is meant “the intended input/output relationship of a system whose purpose is to perform a task” (Pahl et al., 2007). A function is usually expressed by couple noun/verb and the inputs and the outputs are flows of material and/or energy and/or signal. Next, the modular analysis generates the product modular configuration starting from the most detailed level of the functional structure. The obtained modular structure is composed by modules that are commonly intended in the literature as independent building blocks of a larger system (Holtta and Salonen, 2003), they have their own specific function and well-defined interfaces. Then, the product architecture domain represents how these modules and their functions can be concretized. The product architecture is here defined as the arrangement of the functional elements of a product into several physical building blocks, including the mapping of the functional elements to physical components (Ulrich and Eppinger, 2004). The three levels are cross-linked. The structure, traversed downward, highlights how functions and sub-functions are implemented by physical components while, moving upward, the design intent is elicited in terms of functions of the parts and product requirements.
A graph-tree structure (Diestel, 2010), whose nodes are assemblies and subassemblies down to all significant components, representing the product structure is showed in Figure 1. Each tree node is called *block* and stores geometrical and non-geometrical attributes of a part. It contains a name, properties, implemented functions, links to some documentation files. Each *property* basically represents an attribute of the block, such as a geometrical parameter, a material, a specification, a characteristic. The *base property* represents the block as a whole and it enumerates its variants if they exists. A *relation* is a dependency between a property on one side and one or more properties on the other. Relations capture both design choices and constrains between product parts. Screws, bolts, fixtures, wirings are usually neglected as blocks and replaced with relations. Relations are

distinguished between *standard* and *auxiliary*. Those of the first type are intentionally inputted by the designer to mean explicit dependencies. The second type is implicitly introduced to capture the linkages given by the structuring of a product and it consists of three kinds. The first one (*internal relation*) connects the base property with the other properties within a block. In fact, if a base property of a block changes, also other properties are likely to change. The second kind (*assembly relation*) links the base property of a component to the one of its parent assembly. Here, the aim is to capture the implicit link among an assembly and its parts. Finally, the third type (*functional relation*) links properties of different blocks when they implement functions that are connected by a functional flow. This kind of relation links the structure of the product to its functional decomposition. In this way, the framework permits an overall description of the dependencies between components and allows a comprehensive analysis of the changes to be accomplished. Finally, a list of couples formed by a *design context* and the related numerical impact is provided to quantify and store the effect of the modification of a property for various life cycle aspects such as environment, cost, production, noise or vibrations. Each of these values comes to express the impact of changing the property in relative terms towards the impact on the entire product. The value of the impact is an index drawn from designer's experience. Scales and guidelines for the values are shared among designers in order to guarantee data consistency.

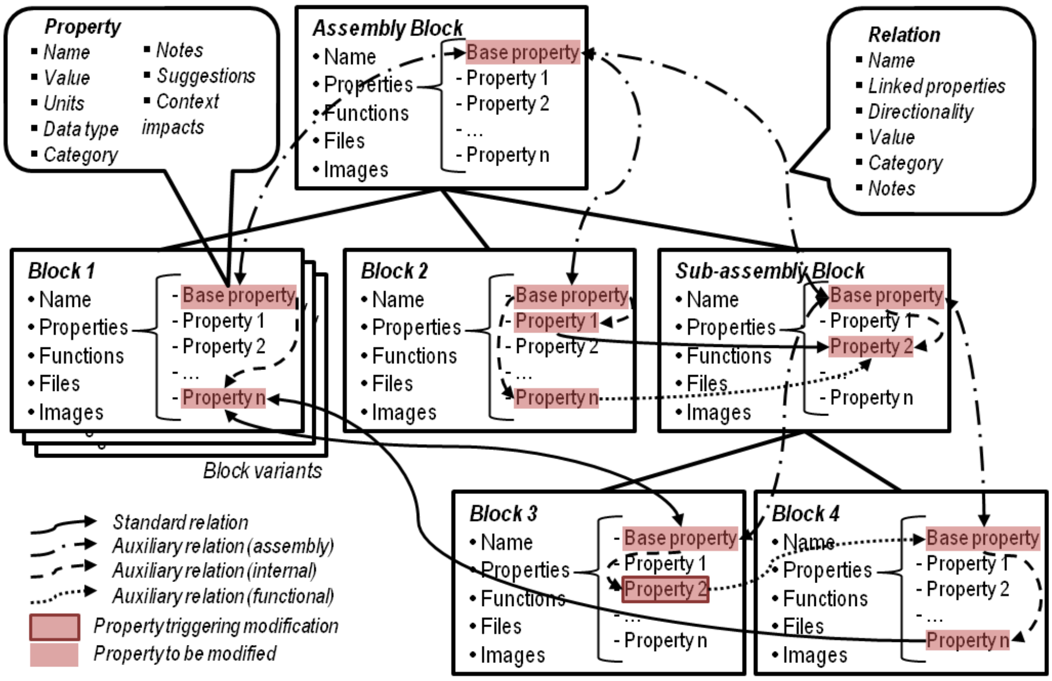

Figure 1. Modulor approach: how the product structure is represented and how a change could propagate

The properties that are directly or indirectly connected to the modification of a part are identified by the change propagation algorithm. No variational solving is employed since many relations simply express qualitative linkages. The algorithm rather traverses the relations until the probability of a modification reaches a fixed threshold value.

Three main steps can be identified in the approach:

1. *Computation of the propagation tree*: the graph formed by properties (nodes) and relations (edges) is traversed starting from the properties triggering the modification. In this way, a modification is iteratively spread from a property to another through the available relations. Given a certain path from a root node, propagation stops when it comes back to a node already visited in the path.
2. *Computation of the probability of change of each property:* once the propagation tree has been determined, the contribution of each node to the global change impact is computed. To this aim a coefficient called *Propagation Contribution Index (PCI)* is defined as the probability of a property to be actually changed as consequence of a certain propagation path. Another factor, called *Relation Probability Factor (RPF)* is defined to compute change probability degradation

in traversing a relation. Given a node i in a propagation path, its PCI_i is computed as follows:

$$PCI_i = PCI_{i-1} \cdot RPF_i \quad (1)$$

where RPF_i refers to the relations group connecting node i to node i-1. PCI is set to 1 for the root nodes. Basically, moving from the initial modification, the parts will contribute with smaller probabilities. Since a property may appear more than once in the propagation tree, its *Global Propagation Contribution Index ($GPCI_p$)* is computed as the sum of the single contributions:

$$GPCI_p = \sum_i PCI_i \quad (2)$$

3. *Computation of change impact indices for each design context:* these are an estimate of the consequences of the modifications for each product life cycle context. The equation to assess them is the follow:

$$I = \sum_b \sum_p (GPCI_p \cdot I_p) \quad (3)$$

where I is the change impact index of the modification for the generic design context, I_p represents how much the property p is affecting the design context for a change of the block b. In other words, I is the sum of the impacts of each property multiplied by the estimated probabilities of changing. The (3) is applied to every design context the company is evaluating.

In conclusion, the propagation algorithm comes out with the list of the components and/or assemblies to be redesigned and the affected properties. The algorithm computes the change impact indices on the basis of the whole relations graph topology.

3.2 Validation of the approach in the industrial context

The introduction of the proposed approach in an industrial context requires some steps to be accomplished. First of all, the product representations must be created and inputted in the system. Then the tool needs to be tuned and validated. In fact, on the basis of past cases of redesign, few parameters must be chosen (RPFs, the propagation threshold, the contexts impacts) according to the expected output. In order to build the product model, significant components are selected starting from the bill of material of the product. The main attributes and the relative impact indices on the design contexts are inputted for each part. These elements allow the product structure to be created. The structure is completed with the relations between the properties. It is important to define physical relations, for instance those due to position or connection, and also linkages due to design constraints. Functional relations are introduced by the system thanks to the flows inserted in the functional representation. The values of the indices representing the impact of changing a property for various design contexts can then be filled thanks to the experience and the know-how of senior designers. Past data about the redesign of previous products facilitate the correct choice of such values.

Once the product representations has been filled in, including the functional and modular ones, the tool has been utilized along the process. This starts with an EC request to the final release of the new product. The general process and some possible variants of it are outlined in the Figure 2. A new design starts from the request of modifications which are validated by the product manager. Once the new features are designed, then they undergo cycles of virtual simulations and redesign until the outcome is satisfactory. Next, a physical mock-up is created and tested. Only if the prototype meets all the expected requirements, the production line can be updated and new tooling designed and produced. Backward loops may occur at different stages: in case of failure of the virtual simulations, unexpected behaviour of the physical prototype, if tooling cannot be realized or is not economical. Such situations require small or wide redesign loops according to the cases. If problems are experienced during the test phase, it is necessary to return on the top of the change chain because the design and the prototyping step have conducted to anomalies that should be corrected.

From this description of the simplified redesign cycle some important elements emerge. The quality and efficiency of the redesign cycle can be measured accordingly to the following parameters:

– the number of iterations needed to reach a correct product and the related production facilities;
– the number of components which are identified as involved in the modification;
– the number of requirements or design contexts being involved;
– the time it takes to execute the redesign process;
– and, finally, the amount of resources employed for the failed tests.

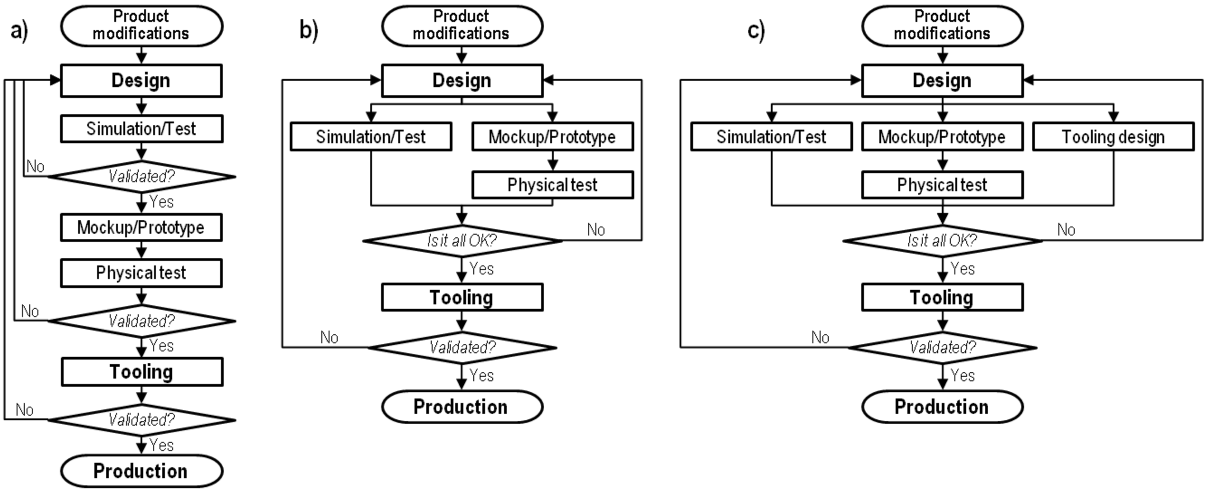

Figure 2. General redesign cycles: a) without or with wide time limits b) with stringent time limits c) with more stringent time limits

The general redesign workflow could change if contextualized in the industrial scenario where time and cost are stringent constraints. So, depending on fixed time limits, it is reasonable to think that some redesign activities must be done simultaneously even if the logical procedure would have preferred a serial execution. For this reason the described process in Figure 2a can be subjected to some modifications. For example the virtual simulations and the prototyping phase could be carried at the same time (Figure 2b) assuming the risk that, in case of mistakes, time is wasted as well as resources, i.e. the cost of the activity in terms of raw materials, equipment and labour. If it is needed by the available time, virtual simulations and physical prototyping can be accomplished along with the tooling design (Figure 2c).

In the next section the Change Management (CM) approach will be validated in a real industrial context with the relative time and cost constraints.

4 VALIDATION IN THE INDUSTRIAL CONTEXT

The validation of the approach has been carried out and tested on the redesign process of a typical electromechanical product, a refrigerator, in collaboration with an Italian large sized company, Indesit Company S.p.a., a leader in household appliances, i.e. washing machines, dishwashers, refrigerators, hobs and ovens. Indesit research and development department is arranged into 4 divisions according to the main product classes. Each section consists of about 35 employees, mainly engineers, which manage the whole product development from conceptual design to detail design and product prototype testing. Marketing operators and stylists collaborate to the process. All technical workspaces are equipped with a CAD system for modelling solid parts and assemblies, an Enterprise Resource Planning (ERP) system integrated with a Product Lifecycle Management (PLM) for datasheet creation and upgrade, product variants store, standard components collection and retrieval, product and component parameters definition. Focusing on the refrigerator department, company statistics show that the technical staff generally manages about 900 design projects every year. Most of them are represented by modifications of existing products. Engineering changes can be divided into two groups depending on their complexity: the *easy* change and the *complex* one. The former involves few components and it is handled in short time. They regard interfacing parts (e.g. dimensions, type of connection) or derives from the replacement of standard components with new ones. On the contrary, a complex EC involves many components and requires the expertise of several designers.

4.1 The modification process under time constraints

The procedure for modifying a product is complex and strongly depends on the nature of the change and on the available time to perform it. The activity has moved from the analysis of the possible workflows. In particular, it has been recognized that the company has a standard procedure concerning product ECs, that is a list of steps to be followed in releasing a new product variant. The proposed CM approach has been introduced in such a process illustrated by Figure 3. The main focus is on the time limits which imposes different internal strategies. Moreover it highlights that different departments are involved in the process and the importance of a fast exchange of information between them. Wrong or delayed data induce iterations and the risk of missing the time limits.

Depending on the time constraints, two main strategies can be followed:

- *Sequential process*, that is the preferred procedure in absence of critical time constraints. It is considered a low risk strategy since each stage can benefit of the results of the previous activity.
- *Simultaneous processes*, when some phases are performed simultaneously. This strategy is adopted when time constraints prevent a standard product development. Typically, the final tests are executed at the same time of the tooling design. Since the possibility to waste time and resources is higher, the company judges this procedure risky.

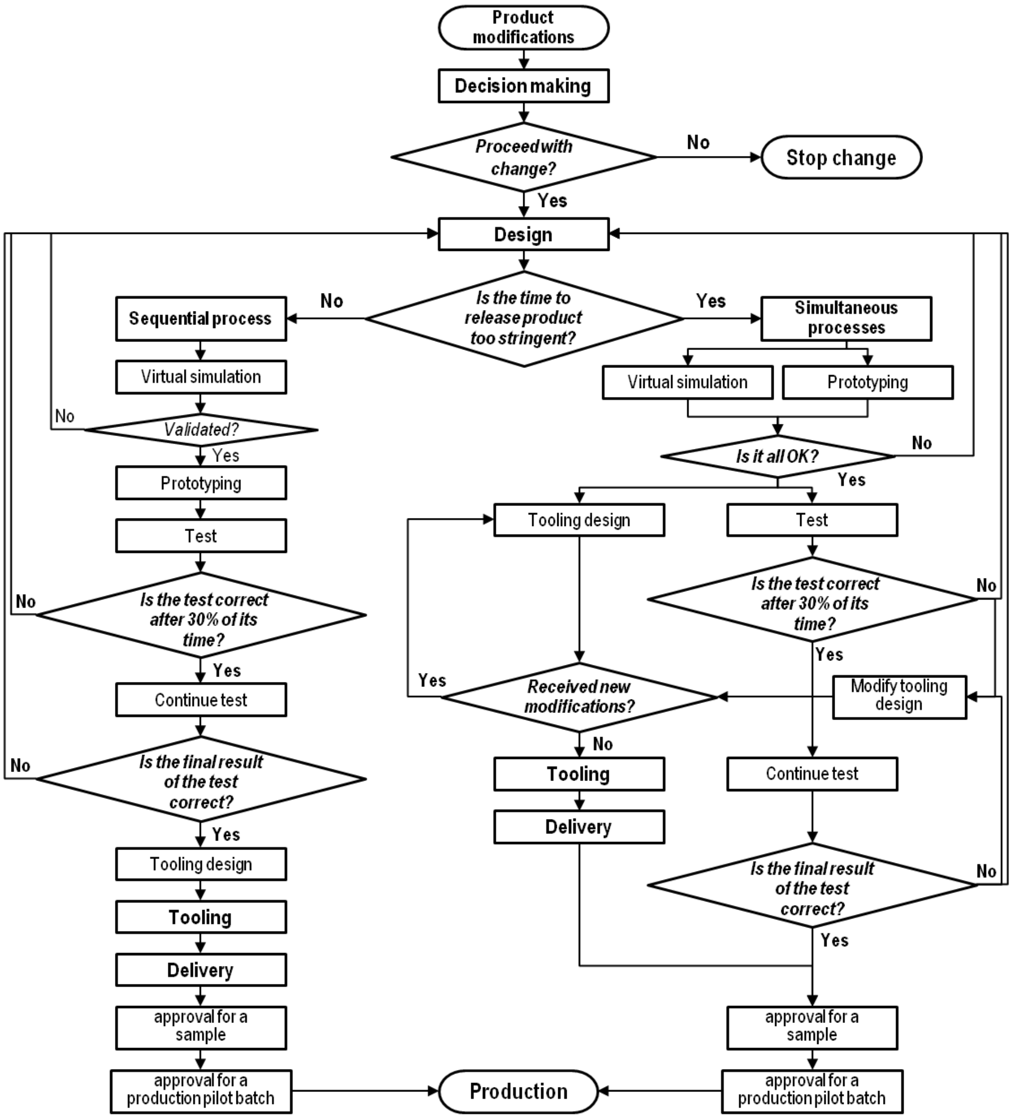

Figure 3. The standard procedure concerning product ECs in Indesit Company

The main involved steps are:

- *Decision making*, by the person in charge to choose whether and how to proceed. In this early phase, the CPM is useful to provide impact indices of the required efforts and workload.
- *Design*, that is the definition of the product to meet new requirements. In case of stringent time constraints the absence of errors is mandatory to avoid iterations. At this stage the CPM must provide a support to retrieve the necessary data to avoid to neglect important design aspects.
- *Virtual simulation*, that is the virtual testing of the product behaviour through simulation software systems. It is closely linked to the quality of the design phase. If design iterations are limited by a better awareness of the product structure, also simulations can be executed in less time and a limited number of times.
- *Prototyping*, that is the physical realization of what has been designed. The prototype allows the

final validation of the product to be accomplished. However, mock-ups are expensive and costly so they must be limited as much as possible.

- *Test*, it involves a series of operations carried out on the product prototype (the finished or the semi-finished one) in order to detect malfunctions or unexpected behaviours. Time spent for this phase is fixed and depends on the amount of tests required by the standards. It is very desirable not to iterate this phase. To this aim, a CPM is advantageous in providing an estimation of possible impacts on requirements that should not be changed.
- *Tooling design* and *tooling*. Tooling includes the needed equipment for the production. It is critical in case moulds are required. Moulds are usually designed and realized by suppliers. The time agreed with suppliers is another time constraint, so only the tooling design can be rearranged to save time. Tooling is the last step before the production starts.

It is a common practice for the company to check the EC process when the 30% of the time to perform the test has elapsed. If something is going wrong then the test is stopped, the problem is analyzed and the design corrected. The analysis of the modification process which has been here briefly described has highlighted the applicability of the change propagation approach described in the previous section. It has been recognized how its outputs are beneficial to several of the described steps.

4.2 Case studies

According to the strategies described in the previous section, two scenarios could happen on real test cases:

– *Optimal case,* that is a situation without limited time constraints. The normal procedure of product development can be followed and the parallel execution of activities that are logically consecutive is not necessary;

– *Case with time limit,* that is a situation where the modified product has a fixed release date. Some steps of the normal procedure of product development are needed to be executed simultaneously. Anyway the designer could use the sequential procedure if he thinks that available time is enough.

Table 1. Some numerical results for the reported case studies

Scenario		Case with time limit			
Change		*Easy* (Lighting of the cell)		*Complex* (More space for bottles)	
Time limit (days)		12		20	
Working group		A (standard approach)	B (using CM tool)	A (standard approach)	B (using CM tool)
Identified components to be verified/modified (initial decision-making step)		6	7	8	14
Computed total impact of the change		-	20%	-	45%
Chosen redesign process		*simultaneous*	*sequential*	*simultaneous*	*simultaneous*
Time (days)	**Design**	2.5	2	4.5	3.5
	Virtual simulation	2.5	1	6	3.5
	Prototyping		1.5		
	Testing	4	2	8	6
	Tooling design and realization		2		
	TOT	**9**	**8.5**	**18.5**	**13**
Process iterations		3	1	5	2
Wasted prototypes		1	0	3	1

The cases of the redesign process of two refrigerator models belonging to the same product family are here reported. Two groups of engineers have been involved in the product development procedure for certain changes. Two engineers has been put together in a group, namely “A”, which has used the standard approach for redesign the refrigerator “A”. Other two engineers were put in the group “B”, which has used the CM tool to implement the same modifications but on the refrigerator “B”. In both groups one member had the responsibility of the choices while the other one had a more technical background. Moreover, the same changes to the refrigerator "B" were assigned to two beginner engineers, who were also provided with the *Modulor* software. In this way it was possible to evaluate how such a tool can facilitate the training of novices.

Easy and complex changes have been carried on to both the refrigerators. In particular, two case studies have been selected: the lamp, considered an easy change, and the refrigerator cell, considered a complex change. For what concerns the lamp change, each group was engaged to search a new solution to improve the lighting quality (i.e. *lighting property*) and to meet new aesthetic requirements. On the other hand, the space (i.e. *geometry property*) of the refrigerator cell would have been modified since the target was to increase the space for bottles. Time limits to release the modified product were fixed for both the products: the first case would have been solved within 12 days while the second one in 20. For both cases the two groups were free to chose the sequential or the simultaneous procedure.

The case studies have shown how the CPM can help the entire team of engineers in charge for the product modifications. Some numerical results of experimental measurements (i.e. identified components to be changed, time spent for each redesign phase) are reported in Table 1.

4.3 Results discussion

While the initial decision-making step, both groups have considered the changes feasible within the time limits and the indicative budget the company had fixed.

A group decided to adopt the simultaneous processes in both the cases. B group adopted it only for the complex change, while the sequential procedure was used for the easy change. In this early decision phase, the CPM made B group understands that it was possible to follow a procedure with much less possible risks. Their decision was supported by the expected limited quantity of components to be changed and by the low levels of impact indices. This choice came out to be appropriate. In fact, during the virtual simulation phase, both groups have found that the new LED lamps did not respond to requests, so they had to redesign the change. However, while B group had only employed some useless working time, A group had also wasted the prototype which was being built. In the second change case, i.e. saving more space for bottles, both groups had initially worked on the refrigerator door. After 30% of the testing activity they realized that a structural problem emerged: the bulkhead was too flexible, and the door began to oscillate too much when the weight to be supported was too high. At this point, A group continued to redesign the door adding a reinforcing rib. On the contrary B group, thanks to the *Modulor* tool, realized that continuing to modify the door were too onerous. In fact, for a modification to the door the software output was severe due to the several connections and dependencies amongst the door and the other fridge parts. So, it was decided to change completely the approach. The space for the bottles could be increased adding a new element, i.e. a new bottle holder to be put inside the cell. Basically, it is a movable shelf which is hung inside the refrigerator cell. This second choice had not led to any further iterations and it has resulted the be the least expensive solution. In fact, it did not require a new mould for the door that would result to be very costly.

The beginner engineers reported some benefits from the use of *Modulor* software. For instance, in the redesign of the lamp some notes stored in the geometric property of the light holder, made them realize that this must be tilted backward to avoid blinding the user. It is likely to assume that this note would have saved an iteration in a real design process and perhaps also a physical mock-up. In addition, they were aware of the same number of components impacted by the changes which were considered by the B group. This number was higher of one unit compared to the components under revision by the A group in the initial stage. In fact, the implications to the electronic board was neglected by the A group causing a slight delay in the design process.

In conclusion, the first advantage of the adopted CPM was to make a designer aware of the total impact which a property modification of a component could cause. The criticality in a product modification is a parameter linked to the time and efforts it takes to meet the change. So it is possible to choose the more appropriate strategy assessing a trade-off between the available time and the risk to waste resources. As the case of the easy change shows, the best procedure which would have had to be followed is the sequential one. In fact no prototypes were rejected and the time constraint were satisfied without recurring to a simultaneous process. At the end, A group, which applied the simultaneous procedure, has even taken more time than B group because more iterations occurred. Moreover, also in the case of complex change, where the chosen procedures were the same amongst the two groups, the results show that there were time saving (till 30%) and less waste of prototypes.

5 CONCLUSIONS

This paper describes a CM approach and a relative tool in order to support the product modification process. It collects heterogeneous product data from abstract, i.e. functions, to concrete, i.e. components, with relative attributes. From such a structure, the tool is able to support the estimate of product change extent and impact. It has been applied in a real industrial context testing its contribution to the improvement of the corporate strategies in product redesign. The main focus was the analysis and evaluation of the method introduced in the redesign process from the early decision making to the prototyping activities. A comparison between the standard workflow and the modified one induced by the usage of the tool is reported to demonstrate its effectiveness. In the household appliances industrial contexts a designer tends to lose the complexity of the dependencies between components. This work contributes to improve his awareness about the consequences of a change. Result in terms of reduction of wasted time and resources in a product redesign cycle are encouraging.

Future works should focus on a dedicated approach for the beginner engineers in order to provide extended knowledge on the product. Moreover, more test cases should be analysed also in additional industrial contexts. Finally, the approach could include a way of suggesting the best change process according to the company strategies and the time constraints.

ACKNOWLEDGMENTS

This work has been developed thanks to the collaboration and funding of Indesit Company S.p.a (www.indesitcompany.com) and Hyperlean S.r.l. (www.hyperlean.eu) which has developed the *Modulor* software package.

REFERENCES

Ahmad, N., Wynn, D. C. and Clarkson, P. J. (2012) Change impact on a product and its redesign process: a tool for knowledge capture and reuse. *Research in Engineering Design*, DOI 10.1007/s00163-012-0139-8.

Brooks, C. and Mocko, G.M. (2011) A method for evaluating manufacturing change in engineering design. *International Design Engineering Technical Conference IDETC/CIE 2011*, Washington, August 28–31, Proceedings of the ASME 2011, pp. 1125-1134.

Cheng, H. and Chu, X. (2012) A network-based assessment approach for change impacts on complex product. *Journal of Intelligent Manufacturing*, Vol. 23, No. 4, pp. 1419–1431.

Diestel, R., (2010) *Graph Theory*. Heidelberg: Springer-Verlag.

Fei, G., Gao, J., Owodunni, D. and Tang, X. (2011) A model driven and knowledge-based methodology for engineering design change management. *Computer-Aided Design & Applications*, Vol. 8, No. 3, pp. 373-382.

Germani, M., Graziosi, S., Mengoni, M. and Raffaeli, R. (2009) Approach for managing lean product design. *17th International Conference on Engineering Design - ICED 2009*, Stanford, California, August 24-27, Proceedings of ICED 09, The Design Society, pp. 73-84.

Holtta, K. and Salonen, M. (2003) Comparing three modularity methods. *Design Engineering Technical Conferences*, Chicago, Illinois, September 2-6, Proceedings of ASME.

Huang, G.Q. and Mak, K.L. (1998) Computer aids for engineering change control. *Journal of Materials Processing Technology*, Vol. 76, No. 1–3, pp. 187–191.

Kilpinen, M., Eckert, C. and Clarkson, P. J. (2009) Assessing impact analysis practice to improve change management capability. *17th International Conference on Engineering Design - ICED 2009*, Stanford, California, August 24-27, Proceedings of ICED 09, The Design Society, pp. 205-216.

Kocar, V. and Akgunduz, A. (2010) ADVICE: A virtual environmental for engineering change management. *Computer in Industry*, Vol. 61, pp. 15-28.

Koh, E. C. Y., Caldwell, N. H. M. and Clarkson, P. J. (2012) A method to assess the effects of engineering change propagation. *Research in Engineering Design*, Vol. 23, No. 4, pp 329-351.

Pahl, G., Beitz, W., Feldhusen, J., and Grote, K. H. (2007) *Engineering Design: A Systematic Approach*. London: Springer.

Raffaeli, R., Mengoni, M. and Germani, M. (2010) A software system for “Design for X” impact evaluations in redesign processes. *Journal of Mechanical Engineering*, Vol. 56, No. 11, pp. 707-717.

Ulrich, K. T. and Eppinger, S.D. (2004) *Product Design and Development*. New York: McGraw-Hill.

Wright, I.C. (1997) A review of research into engineering change management: implications for product design. *Design Studies*, Vol. 18, No. 1, pp. 33-42.