MODELLING AND SIMULATION OF COLLABORATIVE PROCESSES IN MANUFACTURING

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ABSTRACT: This article presents an approach that aims at modelling the collaborative processes encountered in factories within the context of the fourth industrial revolution – known in the specialist literature as Industry 4.0. Collaborative processes modelling is based on the architecture proposed by VDI/VDE for Industry 4.0. This architecture describes the main value chains within a company. In order to validate the proposed models and collaborative processes they were simulated and and implemented using data offered by Compa S.A. as part of FP7 Virtual Factory Framework project.
KEYWORDS: Collaborative processes, Industry 4.0, value chains, manufacturing

1. INTRODUCTION

The fourth industrial revolution or Industry 4.0 [1] describes an evolutionary and progressive industrial production scenario with a significant economic impact. [2]. Industry 4.0 proposes a new level of organisation and control of the entire value chain for the complete duration of product life cycle. The technological basis for achieving the fourth industrial revolution is represented by cyber-physical systems (CPS). The main feature of CPS is that the ICT system is designed together with the physical components in order to maximise total efficacy and is not necessarily embedded in the physical component. Equipped with sensory, computing, action and communication capacities, CPS supplies its local environment or a cloud-type environment with data, information and services [3].

A very important aspect in the context of I 4.0 is the availability of information in real time and the possibility of involving all production instances in increasing added value at all company levels. The collaboration/interaction of people, objects and information systems leads to the dynamic emergence of added-value chains which organise themselves depending on various criteria such as: costs, availability and use of resources. [4].

Within this context, an important mission is to integrate the control and organisation of value chains in the field of industrial automation technology. This integration takes two aspects into account: on the one hand, the functionalities of industrial automation systems which must lend themselves to direct use by the management systems and, on the other hand, the functionalities of the value chain which must lend themselves to integration within the industrial automation systems. Basically, this implies the gradual shift from a centralised architecture to a decentralised one, which will facilitate collaboration [5]. Various architectural approaches are currently being developed, which try to integrate as many I 4.0 aspects as possible.

However, the first stage in developing any I 4.0 representative platform or architecture consists in identifying and modelling the value chains. They are the basis for identifying and defining new business models which will benefit from increased interaction between the different production sub-systems through collaboration processes.

The first part of the paper (chapter 2) presents the theoretical approaches to modelling collaborative processes encountered both in current companies, but also taking into account the specific aspects of I 4.0 systems. Chapter 3 presents the implementation of collaborative processes models and the benefits incurred by the collaborative approach put into practice at Compa S.A. Chapter 4 presents the conclusions of the article.

2. MODELLING COLLABORATIVE PROCESSES

This section focuses on the main value chains introduced by of I 4.0, on the way in which these value chains can be decomposed and structured in collaborative processes, as well as on the identification of collaborative processes that are relevant in the context of these value chains. It highlights the possibility of reusing collaborative models as part of different value chains and the existence of multiple instances of these models in the real context of usage in the company. [6]. The details, reusage and interaction between these

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collaborative processes in accordance with collaborative engineering principles will be explained in the next sections.

2.1. Collaborative processes in Industry 4.0

In I 4.0, associated value chains are united by their artefacts, forming a process model that is similar to the business processes defined in BPML (Business Process Modelling Language). This process model is unique for every production workshop, depending on the variety of possible production structures. It is to be mentioned that the automation of production systems using mechatronic devices / CPS increases exponentially the diversity of production equipment which can be used when implementing them in a production workshop. [7]. A value chain describes the process of value creation throughout the entire life cycle of an asset (material or immaterial product). In the *reference architecture* proposed by VDI (The Association of German Engineers) and *VDE* (The Association for Electrical, Electronic & Information Technologies) for Industry 4.0 [8] as well as in the high level architectural approaches such as [9] four internal value chains are identified, aimed at:

- product management;
- production facilities or infrastructure management;
- production equipment management and
- the management or orders, production of goods and services.

All these value chains imply the collaboration of various factors involved in planning, initiating, executing and monitoring processes. These value chains are also identified in the “classical” processes of value creation [10].

2.2. Modelling in the context of product development

This section analyses and models some of the most important collaborative processes as part of the value chain associated with product development. These are: requirement identification, product design and risk analysis.

This value chain generally describes creating value throughout the duration of product development, from the design stage to the last stage of the cycle, disassembling the product. A production line is clearly separated from the life cycle of a single real product. Usually the “product line” value chain results in artefacts/objects which contain informative items such as a masterplan, production lots, productivity norms etc. However, there are some exceptions, such as demonstrators, prototypes, 3D models, which are conceived and designed as physical tools for development.

The purpose is to obtain a high level of integrating value chains in I 4.0. The important external partners are the users, the communication partners, for example the ones in marketing, sales, after-sales services.

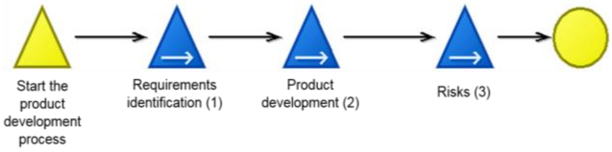


Fig. 1. The main processes as part of the product development process in I4.0

From the perspective of collaborative engineering all these sub-processes are the ones in which the necessity for collaboration between various decision makers is extremely high. These sub-processes are usually followed by prototyping, a process which is specific to the product design value chain. We will now analyse the way in which these products can be decomposed at the level of executable collaborative decision–making processes with the help of existing collaborative technology. A similar approach can be used for the extension of this value chain with disassembling specific activities, which imply the identification of disassembling requirements (partial, total, destructive, non-destructive) and the means of designing this disassembling process. In other words, the product development collaborative process can be reused in the process of disassembling with minimal changes.

Requirements engineering is the field which describes the activities necessary for defining the requirements of a new or a redesigned product by considering the conflicting requirements of the involved decision-makers.

The first stage of the requirements engineering process, also known as *requirements elicitation* implies identifying and formalising product requirements. The requirements are fundamental to any technological product and they describe the necessary functionalities.

Benefiting from factors such as market globalisation, technological progress, client requirement segregation, the product design and requirement identification activities have moved into collaborative working environments as part of the extended enterprise paradigm in the past two decades. It is a fact that up to 80% of a product’s costs are determined by the result of collective decisions made in the initial stage of the product life cycle, namely identifying client requirements.

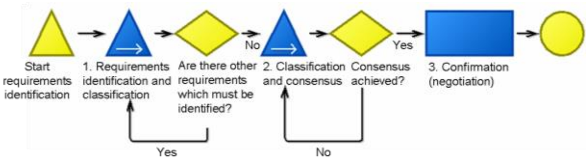


Fig.2. Requirement identification

Due to the collective decision making and to the conflicting objectives, the collaborative process required for making a product is one of the most complex. Developed with the help of collaboration models, it can be applied to any client requirement analysis collaborative process. The principles of collaborative engineering described in the previous section are used In order to reach this goal. The process of requirement identification implies the collaboration of all decision makers interested in making the product: the administrative staff who decide upon the product financing sources and negotiate the functional and non-functional requirements, the end-users, the experts in the respective field, the representatives of the sales and marketing teams, the product developers. Each of these has different requirements and expectations based on their own expertise.

Despite the different perspectives of the factors involved in identifying requirements, their collaboration must lead to a final list of requirements, commonly agreed upon. Therefore, requirement identification is an inherently collaborative process which can be supported by the existing collaborative technology.

2.3. Collaboration in the context of equipment configuration

Besides focusing on the transparency of company resource use, collaborative engineering highlights the involvement of all decision making factors in this complex process in order to put informed decisions into practice adequately. In the case of the main I 4.0 value chains there is obvious collective decision making. Every value chain consists in executing value added processes. Every value creating process can be seen as a composite of production sub-processes which transform certain product entries. The chain of equipment configuration describes the value added throughout the period of production equipment construction, exploitation and disassembling. It includes all the changes, improvements and maintenance-conservation measures. The construction, exploitation, reconfiguration and disassembling of the production system is an essential component of its life cycle. Figure 4 shows the collaborative process of establishing the production capabilities.

As can be seen, it is made up of the sub-process of identifying the premises for establishing the production capabilities, of identifying the optimisation tool used, of collecting data and evaluating configuration alternatives for the production workshop. By using the interaction models specific to collaborative engineering, each of these can be, in turn, decomposed.

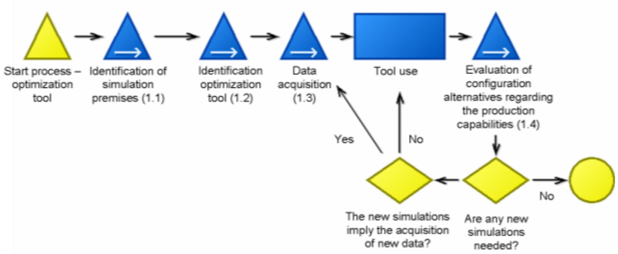


Fig. 3. Collaborative process of establishing the production capabilities

Similarly, the sub-process of data collection is represented using interaction methods specific to collaborative engineering. It is to be noted that regardless of the level of automation through which the production system data are collected and stored, the involvement of the human factor is essential to ensure their semantic interpretation in the real use context.

Just like in the case of the collaborative processes defined above, the process of identifying and collecting data can be reused in the context of any valued added chain, for example for collecting data necessary for using a production workshop layout optimisation tool as part of the infrastructure management chain.

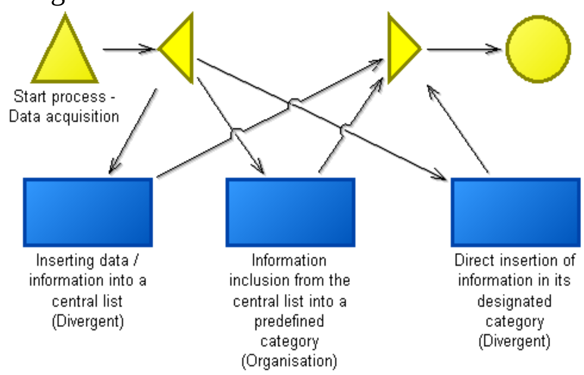


Fig. 4. Collaborative process of collecting data necessary for production capabilities optimisation

Moreover, it can be the trigger of a collaborative process as part of another value added chain. Figure 4 highlights these aspects.

Finally, when having the necessary data and the chosen optimisation tool, the next step is a campaign of simulations which can lead to several alternatives of production capabilities configuration. Every configuration alternative essentially implies acquisitions or reconfigurations of the existing production infrastructure. Figure 5 describes the classical structure of an evaluation module featuring its decomposition elements used in collaborative engineering theory.

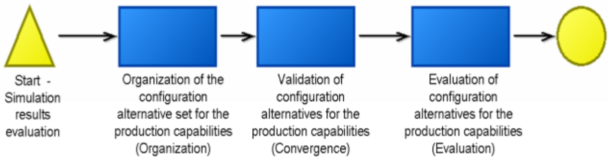


Fig. 5. Collaborative process of evaluating production capabilities configuration alternatives

It is very important for these production capabilities configuration alternatives to be analysed by all important decision makers and for the evaluation process to be reiterated every time there are significant changes in the structure of client orders.

2.4. Reusing collaborative processes and their interaction

In all the examples modelled above the possibility of *reusing collaborative processes* in the context of different value chains was highlighted. Moreover, even if these collaborative processes have been and are still used more frequently as part of a certain value chain, they must permit their interaction in order to optimise the company resources. This means that some collaborative processes require inputs or may be outputs for other processes. I 4.0. is based on the idea that the flow of these collaborative processes is decided upon in real time, based on the specific context, and are not pre-defined like in a classical system of the type Enterprise Resource Planning (ERP) where the processes are pre-set in the form of “best practices” [11]. If in the past these practices were sufficient in order to react to a mostly stable economic environment, in a global competitive environment, where changes are accelerated and discontinuous, they have become totally inefficient. Therefore, it is necessary for decisions to be based on knowledge obtained from all factory levels. In a competitive environment the collaborative decision processes must be adapted quickly in order to address the current opportunities and threats. In conclusion, to do this, companies need to have the possibility to select and test dynamically different collective decision processes in the context of entire organisation interaction and knowledge.

We will now exemplify some possible interactions between the collaborative processes defined above as part of the value chains. The number and intensity of possible interactions are virtually unlimited, which is why only two classical situations will be presented in detail, in which the production value chain requires interaction with the other value chains, especially in the case of production equipment malfunctioning or of changes in product demand structure. For example, in the production value chain the most complex problem is that of assigning the production technological operations, the available equipment, in other words the real flow of transforming the semi-finished products by passing them from one production equipment to another.

Usually, due to the inherent disruptions which occur in the production system (for example: production equipment failure, major departure from the time required for the execution of a technological operation, equipment reconfiguration due to the non-determinism associated with every technological operation etc) this assignment occurs quite frequently in order to take account of the realities of the production context. Figure 6 synthesises the minimal interaction between the production flow and the collaborative processes specific to product development and production equipment development at the time when a malfunctioning occurs.

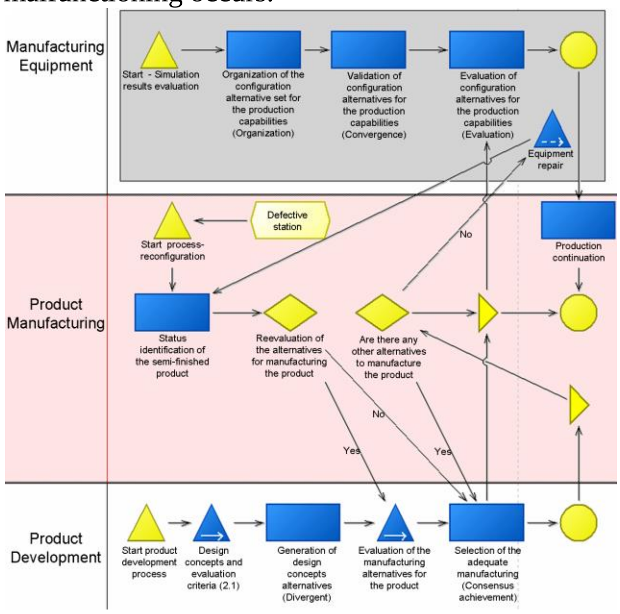


Fig. 6. The interaction of the collaborative processes from the product added value chain with other collaborative processes

Depending on the current state of the semi-finished products the technological processing alternatives necessary for transforming them into end products are evaluated.

Taking into account the unavailability of technological operations due to the faulty machine, efforts are made to identify another feasible alternative for production, namely an alternative technological process. This implies resuming the collaborative sub-process of evaluating the production alternatives or just selecting another technological process from among the ones already identified.

It must be noted that these collaborative sub-processes are associated with the product management value chain and the granularity of reusing these processes (either a single collaborative activity or the entire module) is dependent on the context.

If no feasible production alternative can be identified in the case of unavailability of the faulty production equipment, then the collaborative process of repairing the respective equipment is initiated. In the affirmative case it is necessary to re-evaluate the alternatives to production capabilities configuration and the impact a reconfiguration has on the preset performance parameters. This collaborative process belongs to the value chain specific to production equipment management and consequently implies its interaction with the production value chain.

A frequently encountered situation in current production systems is that in which due to changes in client demand structure (for example a significant increase in demand for a certain type of product compared to another) it is necessary to rearrange the production facilities or to change the production equipment layout in order to minimise the costs of transporting the semi-finished products from one work station to another.

In fact, in I.4.0 it is predicted that this reconfiguration could be achieved dynamically, through standardising the interfaces of a mechanical, electromechanical and IT nature of production systems [11]. The workshop reconfiguration is part of the infrastructure or production facilities management value chain. The production workshop optimal configuration, through the way in which the production equipment is laid out as well as the existence of semi-finished products transport and storage possibilities have an essential impact on the preset performance indicators.

Figure 7 exemplifies the interactions between the processes specific to the value chain production and the other value chains. The need for workshop layout change is usually the result of the process of monitoring and evaluating the preset performance parameters (for example: average duration required for finalising a product, number of products made in a period of time, degree of production equipment use etc.). When major deviations occur, the collaborative process specific to production facilities optimisation can be triggered. This collaborative process is executed in the context of production facilities added value chain, but the model for this process can be taken from the model base of collaborative processes defined above. This context highlights the possibility of reusing the collaborative model defined as part of the production equipment chain. It is to be noted that reusing a model implies only preserving the flow and composite activities structure, and not necessarily its configuration parameters (for example: the group of involved decision makers, the available documents and information).

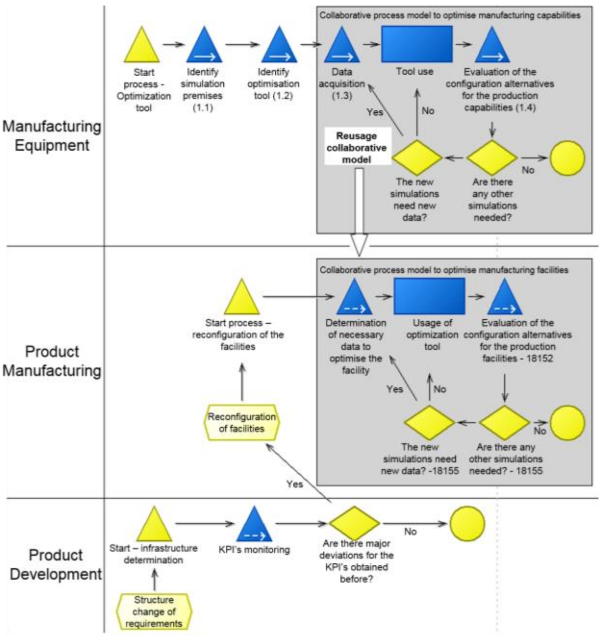


Fig. 7. The interaction of collaborative processes from the production added value chain with those from the production facilities value chain

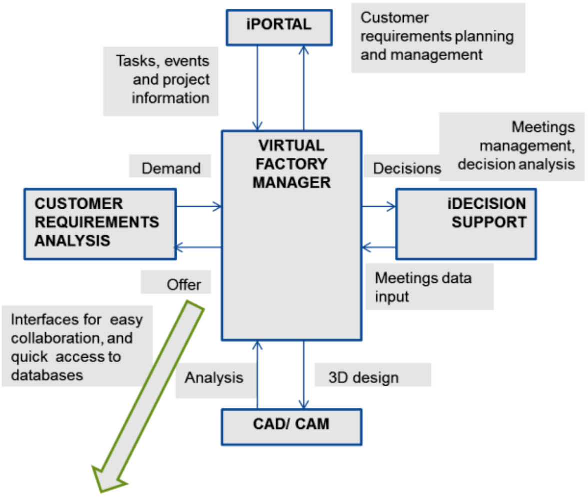
In other words, every collaborative model has multiple execution instances within the factory, depending on the necessity of completing them. Starting from the added value chains identified in the VDI/VDE architecture for I 4.0 and from the principles of analysis and collaboration design specific to group decision support systems engineering, some of the most relevant collaborative processes with a major impact on company resources optimisation have been modelled [11]. Due to the complexity and distinctiveness of the factory collaborative processes analysis, the approach is primarily methodological. What is essential for every company is for the collaborative processes to be modelled, saved and reused when they have the technological infrastructure specific to collaborative working environments. This is why the ADONIS [12] tool has been used for modelling collaborative activities, as it implicitly lends itself to the definition of elements specific to an interaction model or ThinkLet [13]. Moreover, it is developed based on cloud-computing technology, allowing sharing, interacting and reusing collaborative models in the factory.

In all the modelled examples, the possibility of *reusing collaborative processes* in the context of different value chains was taken into account. This is essential to assimilating collaborative work environments in the factory, where the involved decision makers are often unwilling to use new technologies. Even if these processes target mostly the business field, in I 4.0 there is emphasis on the need to also use them in the case of specific processes, where the production equipment operators can contribute information and know-how to the optimisation of factory resources. This is facilitated by the proliferation of mobile devices (such as tablets or smart phones) which can be used by the entire factory staff and which can contribute actively and effectively to the collective decision making processes. The models presented here are examples of some of the most important collaborative processes where collaborative technology can have a significant impact. Due to the complexity and specificity of every company, they must be identified and constantly improved. They must be introduced gradually, as the company current practices assimilate the existing collaborative technology in a positive manner.

3. THE RESULTS OF IMPLEMENTING COLLABORATIVE PROCESSES RELATED TO DEVELOPING A PRODUCT IN COMPA S.A.

This section will present the simulation and analysis of the collaborative processes from the product development value chain for the real case of COMPA S.A., a company from Sibiu. These processes were modelled and simulated as part of the company's participation in the research project FP7 Virtual Factory Framework (VFF) [14]. Thus, the simulation results could be validated with reference to the real data obtained by COMPA in the project. The analysis, simulation and presentation of the implementation of the other collaborative processes are beyond the scope of this article. Further details regarding the models proposed above and which were taken from VFF can be found in [15] and details regarding modelling the value chains identified at COMPA can be found in [16] [17].

During the pilot study that was part of the VFF project, COMPA tested the use of the integrated collaborative environment for the process of requirement analysis only for one flange-type product. A reduction from 11 to approximately 7 days in the requirement analysis time was observed (Fig. 8).



KPI	KPI AS-IS	KPI TO-BE
TIME FOR COMPLETTING THE OFFER	18 DAYS	11 DAYS
TIME FOR DELIVERY OF PRODUCT DESIGN	28 DAY	17 DAYS

Fig. 8. Analysis of COMPA client requirements as part of VFF project

The structure of the used collaborative decision making process is similar to the one modelled in Adonis (Fig. 9). It is considered that all the decisions included in the model implicitly have an affirmative answer, for example: the categories of beneficiaries are known, it is not necessary to identify other requirements, there is consensus among the involved participants. The time allotted to an activity as part of these collaborative processes was approximately 2 hours, the waiting time required for explaining every stage or interaction model was approximately one hour, and the time required for documenting the results of one stage for use in the second stage was approximately 2 hours. Due to the lack of experience of the team involved in using the group decision collaborative system, every decision stage was completed after one working day.

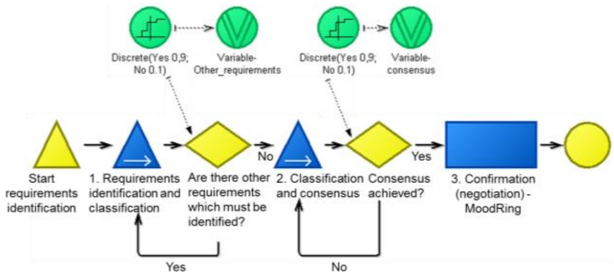


Fig. 9. Adonis simulation

The ADONIS simulation of the described collaborative activities leads to the same result (7 days) required for completion. To simulate the activities, besides the data mentioned above, additional variables for transition conditions were used (decisional elements represented by diamond shapes). These are attributed through a discrete distribution function. As in the VFF project it was considered that all these transitions are implicitly affirmative, their probability was set at 1 to validate the proposed model. Besides, the generic interaction models divergence, organisation, convergence, evaluation, reaching consensus were instantiated with the model used in COMPA. It is to be noted that even if ADONIS offers the possibility to estimate the cost associated to this collaborative process, for reasons of confidentiality their values cannot be made public.

The collaborative process simulation results for the requirement identification highlight the transition variable's major impact on efficiency. The statistical analysis of presented results points to an increase in the collaborative process efficiency by at least 40% as compared to the classical one. This can be explained by the fact that, on the one hand, collaborative engineering minimises the probability of transitions due to the involvement of all decision makers in the decision making process and, on the other hand, due to structuring the collaborative process in clear stages, when a repetitive transition occurs only the relevant activities are completed, without the necessity for the entire process to be resumed. The lower the granularity of these activities, the higher the possibilities of reusing intermediary results and consequently the higher the minimisation of time associated with the collaborative process completion. Even if in the completed simulations only the efficiency of the process was analysed, it is expected that both the efficacity of the process and the level of satisfaction of involved decision makers will be significantly improved.

For frequent use of a decision making collaborative system in a company these values are quite high, on condition that the decision makers already have the necessary experience. Moreover, to maximise the efficiency of collaborative processes it is necessary to use them frequently in the company – the benefits of sporadic use of a collective decision making support system are eliminated by the costs associated with documenting the process and preparing the involved decision makers. The involvement of all relevant decision makers implicitly leads to diminishing the uncertainty regarding completing the collaborative process and to reducing the transitions towards repetitive activities. Collaborative engineering implicitly leads to defining some collaborative activities with lower granularity (numerous and simple activities), thus enabling the reusage of these activities' results in the context of processes that are different from the one in which they were initially designed.

Even if the simulations only aimed at the efficiency of collaborative processes (time required for their completion) the results can be easily transferred both to efficacity (better decisions due mostly to the possibility of processing multiple contributions at the same time) and to the decision makers satisfaction (due to their involvement in all stages relevant to decision making).

4. CONCLUSIONS

Starting from the added value chains defined in the VDI/VDE reference architecture for I 4.0 and from the results of real implementation of collaborative processes as part of the VFF project, a validation of the proposed models was made possible as well as the simulation of an extended set of scenarios, using the models presented in chapter two. Due to length limitations, the paper discusses in chapter three only the implementation of representative collaborative processes related to developing a product in COMPA S.A. Taking into account the generic nature of the modelled collaborative processes, the simulation results can be easily extrapolated to the context of all value chains.

Based on the results of simulations made for the collaborative processes as part of the product development value chain the following conclusions can be drawn:

- in order to maximise collaborative processes efficiency it is necessary to use them frequently in the company– the benefits of sporadic use of a collective decision making support system are eliminated by the costs associated with documenting the process and preparing the involved decision makers;

- involving all the relevant decision makers implicitly leads to diminishing the uncertainty regarding completing the collaborative process and to reducing the transitions towards repetitive activities - as it can be observed from the simulations made, the probability of these transitions has a major impact on the completion time of any collaborative decision making process;
- collaborative engineering implicitly leads to defining some collaborative activities with lower granularity (numerous and simple activities), thus enabling the reusage of these activities' results in the context of processes that are different from the one in which they were initially designed.
- even if the simulations only aimed at the efficiency of collaborative processes (time required for their completion) the results can be easily transferred both to efficacity (better decisions due mostly to the possibility of processing multiple contributions at the same time) and to the decision makers satisfaction (due to their involvement in all stages relevant to decision making);
- in order to increase the efficiency of any collaborative process is it necessary to use mostly the collaborative software tools, otherwise, by having only "islands of collaboration", the impact of any process will be significantly diminished.

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