Functional Requirements for Reconfigurable and Flexible Cyber-Physical System

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Abstract

A truly global market characterized by aggressive competition on a global scale and rapid changes in process technology requires creating production systems that are easy to upgrade, being able to readily integrate new technologies and new functions. In these terms, PERFoRM (Production harmonizEd Reconfiguration of Flexible Robots and Machinery) a European funded project, aims at developing an innovative manufacturing system based on a new agile concept introducing the implementation of methods and methodologies for transforming existing production systems into plug-and-produce production ones based on Cyber-Physical Systems technologies. In particular, this paper aims at describing a methodology leading to identification and deployment of general business and strategic requirements needed to implement new plug-and-produce paradigms into traditional production systems. This approach mainly based on the Requirement Engineering methodology (RE) also leads to the identification of an appropriate set of KPIs (technical and business) able to measure and to benchmark collected requirements. Four Industrial Use Cases have been analyzed, taking the CPS-5C architecture as reference model to map their AS-IS and TO-BE situations with respect to their CPS attitude, confirming the possibility to use this approach among different manufacturing sectors, for large companies, SMEs as well as for new and existing small plants.

Index Terms—*5C architecture, Cyber-Physical System, Requirements Engineering, Methodology, Plug-and-produce, KPIs.*

I. Introduction

Today, industrial enterprises are forced to realize and ensure high level of flexibility and reconfigurability of production systems in order to give a concrete answer to the increasing volatility of market demands and customer requirements [1]. Moreover, the current production systems do not guarantee the proper adaptability to various changing conditions such as volatile market demands, new technological developments or machine breakdowns in terms of automation concepts and architectures. Hence, there is a strong need to identify and to develop within manufacturing industry, a new approach based on plug-and-produce paradigms and Cyber-Physical Systems (CPS) devices aiming at a rapidly adapt production configuration and capacity to the business needs [1].

To cope with functional requirements enabling and ensuring this new manufacturing environment, the implementation of the EU-project PERFoRM has been started [2].

The main objective of PERFoRM project is to combine self-adjusting plug-and-produce devices with simulation, scheduling and optimization methods in order to achieve a flexible manufacturing environment based on rapid and seamless reconfiguration of machinery and robots as response to operational or business events. This objective implies that a new radical approach has to be developed to replace the current ones, available on traditional production systems.

For this reason, a global view of potential deployment of tools and methodologies able to address self-adjustment, correction and control of individual machines and robots, including also their current integration with exiting production systems has to be developed in order to ensure the flexibility and the fast reaction of manufacturing environment to the rapid market changes.

In particular, this paper aims at providing a clear methodology able to identify general business and strategic requirements needed to transform the existing production systems (based on the traditional centralized, vertical and rigid paradigm) into a new system based on plug-and-produce paradigms and CPS architecture. Moreover, this paper targets to deploy identified requirements and to provide an appropriate set of KPIs (technical and business) able to measure and benchmark them. Therefore, the first part of the paper presents the description of the Requirements Engineering (RE) based methodology. Chapter II discusses objectives as well as the relevant phases (i.e. elicitations, analysis, specification, validation), characteristics and constraints. Then, the practical application of this methodology is reported, considering the four industrial Use Cases detailed as the main stakeholders (Chapter III). Chapter IV concerns with the KPIs, their general definition and a description of the methodology utilized to identify them. Afterwards, the Use Case presentation and the results obtained from the analysis are presented, including also an example of the methodology applied to a specific Use Case (Chapter V). Finally, Chapter VI concludes the paper and gives an overview of further work.

II. Process of Requirements Engineering (RE)

The activity related to the identification of the objectives of an envisioned system, its constraints and the assignment of responsibilities for the resulting requirements to different users such as stakeholder, human and devices is defined as Requirements Engineering (RE) discipline [3].

Before making a study of the RE, it is necessary to give a proper definition to requirements, which, following the IEEE definition, can be described as follows: 1) “a condition or capability needed by a user (person or system) to solve a problem or achieve a goal; 2) a condition or capability, which has to be provided by a system or part of a system, to fulfill a contract, a standard, a specification or any other formal documents; 3) a documented representation of a condition or capability, as in 1 or 2 referenced in the first points” [4].

Based on this definition, it can be concluded that a requirement is a need for a physical attribute or functionality of a solution [5]. It describes the capabilities or characteristics a product or service has to provide in order to deal with a specific problem [6]. In order to reduce the risks of misunderstandings and erroneous implementations during a specific project, according to Pohl [5], the most relevant quality criteria parameters that have to be guaranteed for achieving a "good requirement" are: Unambiguity; Understandability; Completeness; Consistency; Verifiability; Traceability; Relevancy; and Feasibility.

Following the definition, requirements describe only the conditions or capabilities of the solution, but it does not consider the approach to be provided. Thus, the requirement and the form of the solution should be considered to be strictly separated.

The term Requirements Engineering describes the processes leading to the production and management of the requirement definition [7]. This process does not consist of just analysis: it involves eliciting relevant knowledge, understanding the task and its social and organizational context, the scope, the contents and the language, resolving conflicting requirements and synthesizing appropriate structures for describing the results. The use of the term Requirements Engineering has been proposed to indicate the complexity of this process [7].

Based on literature studies [6],[8], the RE main phases are listed below:

- Requirements elicitation (take-up of requirements for a solution to a problem);
- Requirements analysis (checking requirements and stakeholder conflicts);
- Requirements specification (documenting the requirements);
- Requirements validation (validating whatever the proposed solution meets the requirements).

Requirements Elicitation involves the extraction and representation of information taking into account all potential stakeholders, their goals and their motivation in order to improve the precision and the accuracy of relevant requirements identified for the development of a solution [7].

Nevertheless, there may be several discrepancies, such as lack of understanding, incomplete definition or inconsistency. For this reasons, the goal of next phase (Requirements analysis) is to evaluate if each requirement elicited describes something that is "necessary, verifiable and reachable" [9].

In order to consolidate the information coming from the previous phases and to be aligned with stakeholder views, during the Requirements specification phase, requirements are structured in a suitable way, that could be readable and understandable by anyone that has not been involved in the previous steps and that could provide a complete description of the solution that has to be developed [8].

The specification must be validated with regard to the original needs of the client (stakeholders). Hence, the main focus of Validation phase is to prove that the solution proposed after the Requirements Specification phase effectively meets the specified requirements [7]. Therefore, the stakeholders have to be involved in a second review of the requirements in order to identify the faults in the previous steps, to correct and to validate them providing the final results.

III. SPECIFIC USE CASE ANALYSIS METHOD

For each Use Case, the requirement definition process has been carried out following the aforementioned RE methodology. In particular, Fig. 1 describes the RE-based approach utilized within this paper.

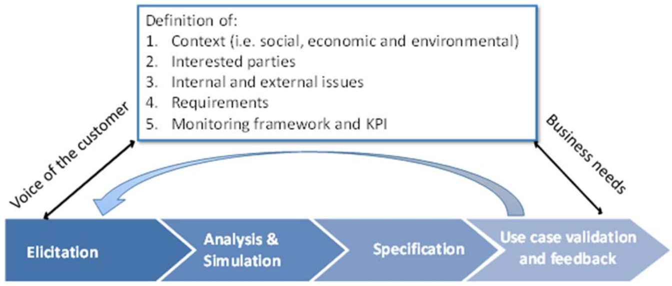

Fig. 1 Requirements Engineering in PERFoRM [10]

The first step is the **elicitation phase** through which the description of the overall context is identified. It includes the end-user and other stakeholder descriptions in terms of technical, physical, social and organizational environment. Based on this, first requirements are derived from all stakeholders' goals and tasks, their current processes and similar systems and products. Among the different techniques proposed by MSEE [10], during this step a suitable form is utilized to help to elicit useful requirements. The form is prepared for each Use Case and its questions are arranged in groups dealing with a single topic or functionality. For each of these groups, a number of representative questions can be defined in order to capture qualitative as well as quantitative data.[11]. The main objectives of such question groups can be collected in the following points as shown in Table 1:

- Description of AS-IS and TO-BE end-user scenarios: The scenarios should describe the inputs, outputs, activities and entities of the current and the proposed ecosystem in order to understand the existing problems of the company and to reach sufficient knowledge of the current status for developing a migration strategy for the new scenario.
- Identification of stakeholders, technologies, legacy systems: The relevant stakeholders, technologies and legacy systems from the ecosystem scenarios have to be described to be considered in the solution design.

TABLE 1

FUNCTIONAL REQUIREMENTS - QUESTIONNAIRE TEMPLATE

FUNCTIONAL REQUIREMENTS	
AS-IS	**Industrial Partner:**
Summary and scope of the project	
Business Scenarios	
Technical aspects (i.e. main products and services, markets)	
Main involved processes, main involved teams & roles	
Infrastuctures: Shop Floor, Server, Network, Applications ...	
Social and organizational issues, (job enlargement, teamwork, involvement, etc..)	
Economical issues	
Environment	
Interested Parties and Internal/External Stakeholders	
Internal and external issues	
TO-BE	
Identify goals	
Identify relevant processes and tasks	
Stakeholders' expectations	
Constrains and possible obstacle/limitations	

The following phase consists of the **Requirements analysis**. During this phase, the user requirements, extracted from the scenarios and processes, have to be understood and discussed among all parties that are involved in each Use Case [10]. It has to be documented what is technically and economically in scope with the project and different aspects have to be taken into account in order to provide a maximized set of requirements. The first analyzed aspect is related to stakeholders. In particular, their homogeneous spatial distribution and their temporal availability to conduct elicitation process are evaluated. Then, the complexity of solutions, the potential need to make a radical innovation and the evaluation of timing necessary to reach such innovation are taken into consideration [6]. Finally, taking the quality criteria proposed by Pohl [5] into account, the different types of requirements are classified with the following clusters: functional and non-functional requirements.

Knowing that the RE methodology has the objective to identify the main relevant requirements that have to be accomplished, it is essential to specify which needs such requirements are related to. For this reason, **Specification phase** (the third phase of RE methodology) has the objective to translate into an understandable form the stakeholders' requirements coherently with the main company objectives, in order to get the comparison of homogeneous contexts feasible. In this case, the 5C levels CPS structure, proposed by J.Lee [12] has been taken as a reference model to show the coherency between the use case requirements and the project objectives (flexibility and reconfigurability). In fact, this pyramid, called also 5C architecture, provides the five levels of CPS functionalities whose implementation can ensure the system to obtain a fully flexibility and reconfigurability.

In other words, after having identified the use case requirements, it has been possible to match them with 5C levels and so to understand firstly the principal requirements that has to be achieved and then it has been possible to understand how many steps are needed in order to reach the fully flexibility and reconfigurability, locating both AS-IS and TO-BE situations with respect to their CPS' role.

According to J. Lee, the proposed 5C structure is composed of five levels that are listed below and are shown in the Fig. 2

- Smart Connection;
- Data-to-information conversion;
- Cyber;
- Cognition;
- Configuration.

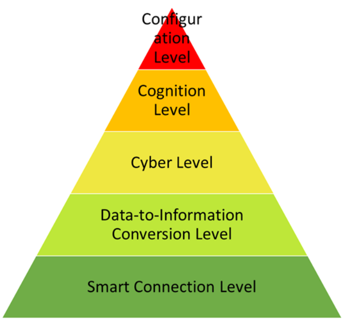

Fig. 2 5C architecture for implementation of Cyber-Physical System [12]

Smart connection

This level includes the ability to manage data acquisition systems and to transfer it to central server through proper sensors, data sources and transferring protocols, hence, ensuring the condition monitoring activity of shop floor level [12].

Data-to-information conversion

This level consists on the ability to obtain the self-awareness of machines trough intelligent algorithms enabling data mining and data processing first and calculating health value and estimating remaining useful life then. This level also involves the possibility to transform data coming from previous level into valuable knowledge [12].

Cyber

The cyber level refers to activities aiming at obtaining better status of the whole fleet through comparison and analysis of data coming from individual machines. This level can also be considered as information cornerstone of this architecture as it receives data from what happens at machine level in terms of their status and their behavior. Finally, this level provides data to Decision Support Systems (DSS) grouped in the next level [12].

Cognition

Since comparative information as well as individual machine status is available from the lower levels, in this level it is possible to have an overall perception of production system. As a result, it becomes possible to generate a thorough knowledge of the whole monitored system providing the possibility to prioritize the decisions and to select the most suitable through DSS [12].

Configuration

The configuration level involves the ability to provide feedback from cyber space to physical space and to apply preventive and corrective decisions taken from previous level [12].

Hence, each industrial partner has been analyzed and positioned on the proper level according to its initial condition (AS-IS). In this way, starting from the Use Cases' needs, during the specification phase it was possible to identify their main requirements and to select the final level (TO-BE) linked to those requirements.

Finally, the last phase of the requirement definition process consists in the **Requirement Validation**. The main goal of this task is to derive leading directions from the previous tasks, in order to properly define the context, and to identify functional and non-functional requirements, based on objectives, relevant processes and involved stakeholders. This iteration is run through following table fulfillment according to the attached legend. Here, the relevant processes are investigated; the requirements are classified as functional or non-functional; priority is defined as high (i.e. *must have* or within the scope of the project) and low (i.e. *nice to have* or beyond the scope of the project); KPIs are categorized into classes, types and relevant trends (i.e. monitored at different stages if the project, to verify effectiveness of the results).

TABLE 2

SECOND ITERATION: VALIDATION PHASE

ID	Process (1)	Stakeholder	Requirement definition (2)	Type (3)	Priority (4)	KPI (5)

Legend

1. **Processes**: core processes (product/service realization) and support processes (risk assessment, planning, HR management, document control, sales, design and development, procurement, product/process monitoring, continual improvement, etc.);
2. **Requirement definition**: technical aspects (materials, machines, methods), environment, social factors, economic issues, infrastructure;
3. **Type**: functional, non-functional, others;
4. **Priority**: high, low;
5. **KPI framework**, related to classes (e.g. cost, customer satisfaction, etc.), types (as-is, to-be, target), trends.

The main output of this methodology is to have a straight collaboration with each use case partner. In fact, this methodology allows to realize a focused analysis of the specific processes involved in the project, to recognize the specific person, organization and department that have a potential interest on each process, to understand the problem that arises from the needs of stakeholders and, therefore, to identify the final requirements and their performance indicator.

Furthermore, this methodology allows to classify each requirement (through Priority taxonomy), identifying which requirements are really important according to the specific use case perspective. This research task will lead to the identification of both general requirements, which are necessary for a successful implementation of reconfigurable system, regardless of the Use Case, and specific requirements, which are use-case dependent.

IV. DEFINITION AND EVALUATION OF RELEVANT KPI

As far as KPIs are concerned, several definitions are available in literature [13], [14]. A performance indicator may be defined as "a quantified data which measures the efficiency of decision variables (as a quantity that the decision-maker controls) in the achievement of objectives, defined at a considered decision level and in coherence with the defined business strategy"[13]. Most methods identify relevant KPIs by sorting out performance indicators based on objectives, thus resulting in a significant number of parameters, which are not necessarily consistent at different levels of the organization.

For this reason, during this study a proper approach originated from ECOGRAI in combination with a performance indicators reference list derived from the Value Reference Model (VRM) has been applied [15]. In fact, ECOGRAI is based on the triplet (objective-decision variable-measure) so as to design and implement a system of performance indicators in all centers of power that is focused on evaluation and at the same time coherent with the branching of objectives (Fig. 3) [14]. This method is organized according to the following steps:

1. Identifying objectives assigned to the decision makers.
2. Determining the processes and the associated variables (called "Drivers") on which the decision makers can act to reach their objectives.
3. Sorting out Key Performances Indicators which are related to the objectives and variables.

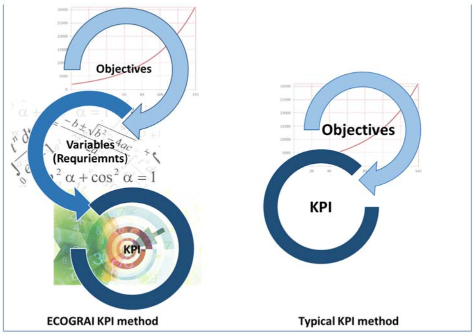

Fig. 3 MSEE (ECOGRAI) KPI and typical KPI methods, adapted from [13]

Therefore, this method has been selected to properly identify effective performance indicators related to the different Use Cases. For each of them the relevant processes and interested parties (internal and external) have been identified within validation table in order to determine a consistent set of indicators, which are worthwhile for all Use Cases.

Finally, a limited set of KPIs have been defined taking into account those indicators that are more related to each Use Case objective. Such performance indicators will be managed by an appropriate framework to carry out the necessary evaluation and deployment on the Use Cases. The framework will essentially consist in a classification of KPIs according to different categories:

- Productivity (e.g. throughput, MTBF, MTTR, etc.);
- OTD (e.g. On Time Delivery);
- Quality (e.g. scrap rate, FPY, etc.);
- Flexibility (e.g. set-up/change over time);
- Costs and administration (e.g. ROI, PBT, etc.).

V. USE CASE ANALYSIS

In order to identify and clarify the functional requirements, especially in terms of flexibility and reconfigurability as well as their relevant measurement metrics (KPIs), four industrial Use Cases have been analyzed. They represent four key European industrial sectors, which are white goods, aerospace, automotive as well as industrial machinery respectively. In particular, they assemble four objectives that require both flexibility and reconfigurability improvement as shown below:

Objective 1: To increase utilization and throughput using a production system made of several flexible and reconfigurable micro-production flow cells;

Objective 2: To establish a real time monitoring system able to correlate KPIs and KBF (Key Business Factors);

Objective 3: To reduce delay due to maintenance downtimes, moving from reactive to proactive maintenance;

Objective 4: To make available low cost automated flexible assembly line to rapidly start manufacturing of efficient products adapted to local needs;

In order to provide an example of the use case analysis, the validation table related to Objective 2 is reported. This table shows the requirements definition, their connection with both specific stakeholders and involved processes, their classification in terms of typology and priority and their performance indicator.

TABLE 3

VALIDATION TABLE: USE CASE APPLICATION

Process	Stakeholder	Requirement definition	Type	Priority	KPI
Cavity fabrication (stamping, welding, painting, etc)	Production Quality Maintenance Industrial Engineering HR ICT	Simulation	Funct	High	Sensitivity Analysis
		Process interactions	Funct	High	Sensitivity Analysis
		WIP optimization	Funct	High	WIP %
		Reconfigurability	Funct	High	C/O time and costs
		Efficiency	Funct	High	OEE
		Reducing downtime and time to repair	Funct	Low	MTBF, MTTR

The framework used to identify ECOGRAI triplet is depicted in the picture below. It shows different levels of requirements considered as decision variables that lead to the achievement of *Objective 2.* In particular, it is possible to identify that the ability to create *model and simulation* of global factory behaviour is one of the most relevant functional requirement that leads to improve *Production Optimization* and *Reconfigurability* needed to reach such Objective 2.

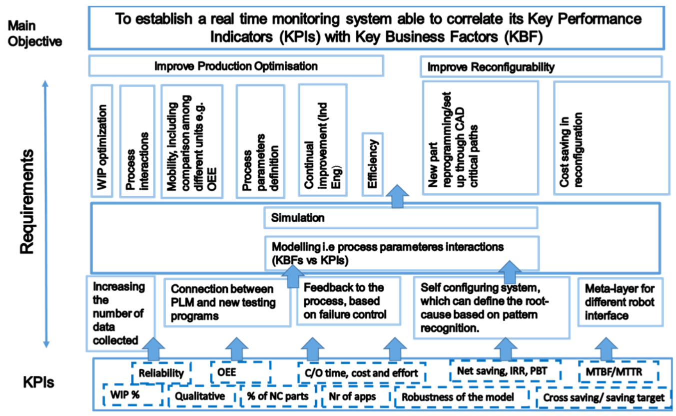

Fig. 4 Framework for requirements and KPIs identification for Objective 2

After analyzing each objective, each context and constraint through RE application, the overall results of all Use Cases can be summarized in Table 4 that shows the General Requirements and the Others Requirements. The former is related to those requirements identified for all objectives and for all sectors and which directly allow flexibility and reconfigurability of a system. The latter identifies the requirements needed to obtain such flexibility and reconfigurability. In particular, the table below consolidates acquired results. According to this, the flexibility can be granted by developing the ability to quickly change raw materials, processes, and cycles, and reducing change over time. On the other hand, the reconfigurability can be obtained through the ability to manage feedback and data from process and production departments.

TABLE 4

GENERAL REQUIREMENTS: FLEXIBILITY AND RECONFIGURABILITY OVERVIEW

General Requirements		Others Requirements
Flexibility	**Reconfigurability**	**Necessary to flexibility and reconfigurability**
-Ability to Change Raw material -Ability to Change Processes -Ability to obtain Process interactions -Agility production -To facilitate Mobility, including comparison among different units e.g. OEE, micro-flow-cells) -Cycle time reduction -Cycle , cost reduction	To obtain feedback from production to design To obtain Final test feedback to Robot system configuration To obtain feedback to the process, based on failure control Cost saving in reconfiguration To obtain new part reprogramming/set up through CAD critical paths Self-configuring system, which can define the root-	100% Traceability and identification of single products up to the supply chain
		Ability to enable Simulation, Model and prototype in the CPS environment (i.e. process parameters interaction, global factory behaviour, predictive failure)
		Increase the amount of data collected and data availability
		(Semi)-Automatic data gathering of machine condition

	cause based on pattern recognition. Set-up time reduction	Full integration and quick communication among different departments and functions (i.e. scheduling and maintenance systems integration, production and process planning,)

VI. CONCLUSION

The relevant objective of this paper is related to the description of a proper methodology to identify and deploy general business and strategic requirements for reconfigurable and flexible manufacturing environment, providing the measurement and benchmark of KPIs adapted on each Use Case proper reality.

For this reasons, a methodology derived from RE has been proposed. It essentially consists in four main steps (i.e. Elicitation, Analysis, Specification and Validation) and it has been carried out through an iterative exercise in order to first identify the requirements and then to validate them. In particular, the proposed methodology has been adopted for all Use Cases in order to realize which requirements and KPIs are essentially to be implemented and benchmarked in a flexible and reconfigurable production system, and to evaluate their consistency with the CPS framework.

According to this framework, the 5C architecture was utilized to map the current Use Case level (AS-IS) and the future situation (TO-BE) related to their objectives and enabled by PERFoRM project activities, as summarized in the following picture. This approach can be considered dynamically, meaning that by changing either objectives or constraints, requirements can be fine tuned in the next project phases coherently.

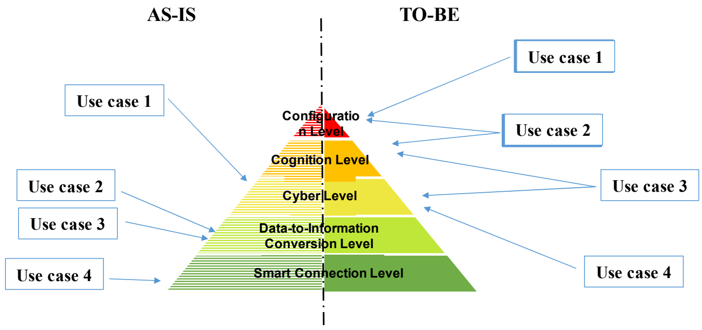

Fig. 5 5C architecture: Use Case overview – adapted from [12]

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