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A new agile hybridization approach and a set of related guidelines for mechatronic product development

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Abstract. In industry 4.0, the growing incorporation of cyber-physical systems (CPS) into manufacturing facilities composed of mechatronic products brings forth the need of reducing development cost while maintaining the quality and in parallel the need to adapt changes along the lifecycle of the product development. Most of the traditional development methods fail to solve such new challenges. However, some agile methods, widely used in the software industry, could meet these requirements. It is then essential to identify the criticalities of agile methods regarding mechatronic system development specificities.

As a result, our research work focuses on combining traditional and agile approaches to improve mechatronic products development in a changing market context. The development of hybrid approach is based on the analysis of traditional, agile methods and consideration of challenges in the development of mechatronic products. To illustrate the advantages of such hybridization, we propose a first hybrid approach consisting of some elements of the Scrum method (the most popular agile approach) into the V-Model. Differentiating advantages of this new approach, compared to other agile methods, include the freedom to propagate necessary changes in product architecture during the development of its different modules.

This new approach focuses on the hybridization of traditional and agile methods and the required guidelines to adopt and use for enhanced mechatronic products development. These guidelines are the base for changing the organizational culture and values which were previously associated with traditional development approaches.

Keywords: Mechatronic products development · Hybrid approach · Agile approach · Scrum · V-Model.

1 Introduction

The new era of industry 4.0 requires us to use various information technologies in order to fulfil the goal towards automation and smart factories. In order to reach that goal, industries demand a new approach for more efficient product development, especially for the mechatronic products as they can be backbones of IoT and CPS. A common goal of industry 4.0 steers everyone towards the most effective interaction of the machine, internet and human for creating a better environment for production. Which also make us stumbled upon to the problems like the uncertainty of the market, complexity, continuous change in the requirements. The traditional approach, which provides rigidity to the product development based on sequential processes, usually in a top-down framework and with a fixed team structure [1], has been inefficient, thus the need for more flexible product development methods leads industries towards agile approaches. The research issue is then how to take a result, the aim of this research is to provide hybrid approaches to develop mechatronic systems by combining agile and traditional product development methods. Extensive literature research and semi-structured interview method allows extracting the information on agile methods, its use in the development of mechatronics product development and its crucial aspects for adoption as well as the use of a hybrid approach. This research helps to break down the steps during mechatronic product development and to assign the agile approach to relevant phases. Finally, in order to provide flexibility in product architecture and modules design, the hybridization of the V-Model with Scrum is presented.

1.1 Industry 4.0

Industry 4.0 arises from the increased complexity in the product, the market customization, the drive towards digitization, the ubiquitous internet and the global competition to produce a better product in less time while reducing the human interaction with the production facility. This term was coined in Germany in 2011 to revolutionize the production system with the help of the internet, rapid prototyping techniques, artificial intelligence and cloud computing [2]. Other reasons to focus on industry 4.0 was to improve the communication between machines and humans. The fascination for this aspect is to reduce human errors, maximizing the efficiency of the machines with human skills in problem-solving and strategic decision making [3].

Two crucial elements of industry 4.0 are the Internet of Things (IoT) and cyber-physical system (CPS).

Internet of Things (IoT). Development of various technologies such as sensors, internet, Radio Frequency Identification (RFID) technique, computers can be utilized for realizing dynamic interactions between machine to machine and human to machine [4]. Transparent sharing of information while providing security and using one common language are the important issues of IoT which need to be addressed [5].

Cyber-Physical Systems (CPS). Using mechatronic systems to automate the production facilities using a network will help reduce human error [6] and support the

concept of a dark factory with full automation [7]. Modelling of this complex system requires a communication across various disciplines and a more flexible development method in order to reduce uncertainty and cost of detailed modelling [8].

1.2 Traditional Product Development Methods

Traditional product development methods provide sequential, plan-driven and organized approach and are well suited for the product development when requirements are fixed. Traditional product development methods affect project management activities too such as strict scheduling, fixed budget allocation, documentation and tracking [9]. Here are two of the most common traditional product development methods.

Stage-gate method and waterfall. The Stage-gate method, also known as a Waterfall method (referred to in the IT sector) has a linear structure with definite stages. Each stage requires inputs from the previous stage. Over the past two decades, the Waterfall method has been criticized for being too rigid. While for software product development, the incremental output is essential to know the unforeseeable problems which arise in the middle of the development process, the waterfall model fails to provide this incremental output [1, 10, 11].

V-Model. V-Model was encouraged to be used in mechatronic product development. The difference between the V-Model used for software product development and V-Model for mechatronic is the disintegration of function for development purpose and again integrating it in the testing phase [12]. This difference is due to the multiple domains in the mechatronic system. Though it is known for its plan-driven approach, it contains iterations for refining the results [12]. An example of the V-Model is shown in Fig. 1.

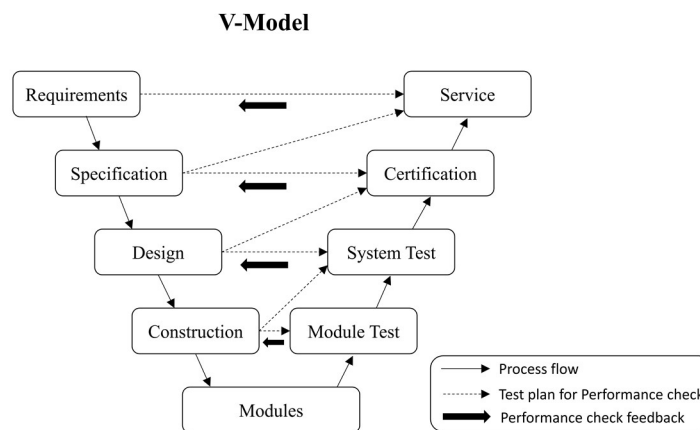


Fig. 1. V-Model [6, 13]

Unlike an agile approach where product requirements are not entirely fixed, in a traditional approach, detailed requirements are given by customers in advance before planning the project. This approach is linear and process-oriented with exceptional long iterations. Organizational structure is also hierarchical; centralized authority steers the project by keeping control to most of the activities. Communications are mostly formal, which needs to go through proper channel and keeping authorities in the loop. Formal statements are crucial while transferring the knowledge which makes knowledge transfer process too bureaucratic. Also, reporting of work progress to the only manager and not the whole team creates misunderstanding within the team about work. Another difference is that the traditional approach is a document-based [14, 15].

1.3 Limits of Traditional Product Development Methods

Though traditional product development methods have served the industries well in the last few decades, they failed to fulfil an essential requirement to avoid uncertainty and to provide flexibility during product development [1]. Few disadvantages of the traditional approach are, not suitable for breakthrough innovation, governance of the project cannot be changed over a long period, change in requirements cannot be adapted, tangible product can only be seen at the end, the consideration for uncertainty is null or very low, no measure of performance is available in the middle of the process, cost and time for each stage is not definable, the feedback from testing can be generated only at the end [1, 13, 16–19].

2 State-of-the-Art

In order to provide a hybrid framework comprised of different methods, it is essential to study specific methods and their important aspects. This chapter describes the agile methods. It also explains the criticalities in mechatronic product development which will be used for deriving requirements for creating a hybrid approach for multidisciplinary product development.

2.1 Agile Methods

Based on the values of agility such as individuals and interactions over processes and tools, working software over comprehensive documentation, customer collaboration over contract negotiation and responding to change over following a plan, [20] software industries have been successfully developing products in a flexible manner. Customer integration within the product development process and iterative development cycles are the backbones of the agile methods. Some of the agile methods are as follows:

Scrum. Scrum is the most popular method in product development [21], as it provides an easy adaptable framework in any industry and its features are not just limited to software development [22]. Application of Scrum for hardware product development

starts with changing the mindset included in traditional approaches, and instead of keeping complete internal control over the process and outcome, customer has to be involved in each iteration to provide feedback and eventually propose some requirements changes. Instead of a hierarchical structure of a team, self-organizing team and transparent organization need to be provided [22]. While implementing Scrum for hardware product development, few constraints need to be considered and worked on such as definition of the “done” (deliverable), multidisciplinary team structure and integration of different developed modules from different disciplines in case of Scrum of Scrum.

Kanban: Kanban is an agile product development method with no iterations but only increments in the product. This term has migrated from the logistic application, where it was used to show the availability of material and keeping the inventory at an optimum level. Kanban method works on a continuous run of completing the task in a to-do list. Kanban has no specific framework, which makes it ideal to use it in any phase of an innovation process [23].

The backbone of this method is its tool, Kanban board. This tool helps the team visualize the progress at each phase. It uses cards with tasks written on it, in a column which describes the status of that task.

Other agile methods are Feature Driven Development (FDD), Design Thinking, Extreme Programming and Hackathon [23]. Most of the agile methods are not suitable for hardware or mechatronic product development as well as for the mass production [24]. Along with this, a change from traditional to agile is difficult as the employees have the mindset developed from traditional approach. For Scrum, framework is easy to understand but hard to follow due to lack of self-discipline [22].

2.2 Hybrid Approach

Many academics in this field have researched about hybrid approach along with the creation of a framework. One research paper has described the Scrum method with Model-Based System Engineering (MBSE) to make MBSE more reliable and flexible. It is a Scrum method with the addition of three main aspects: black-box analysis, white box analysis and physical prototype increment. In this framework, black-box analysis is used for an analysis to build the requirements by exploring all the views in agreement with the customer. This analysis is included to reduce the further changes in the product backlog, which is an essential point as changes occurred later in hardware or mechatronics product development are costly. White box analysis recognizes the architecture of the system with the prioritized set of functions which are defined in the black-box analysis. In this analysis, components are allocated for connecting the architecture with those functions. In the end, those incorporated components are validated as per the requirement set in black box analysis [25].

Another research in hybrid approach is a vertical agile approach which focuses on the development of mechanics with traditional method and informatics and electronics with agile method simultaneously. Integration of the outcome of each cycle from the agile approach into the traditional one is challenging and requires efforts in communicating [12].

2.3 Criticalities in Mechatronic System Development

Combining constraints, knowledge and more importantly, teams from more than three different domains is difficult. Technological advancement in each segment is at a different pace from other segments. There are many challenges in the field of mechatronic which are categorized into two areas, product development and organizational. Few authors have described the challenges in mechatronic which are listed as follows [6, 26–29].

Product and development process related: Long development duration, product complexity, large number of modules, technological innovation at a different rate in a different segment, fast pace of innovations in software and electronics, life of each element is different, upgrades frequently needed, product customization, changes in requirements, ineffective product development process, challenges of adopting agile, verification of physical prototype is expensive, computational analysis in the design phase is expensive, dependency on a supplier for design affects virtual testing, one design tool to integrate the design of each element, meeting design requirements in the final product, unpredictable behaviour of a virtual prototype.

Organizational related: communication within a multidisciplinary team, synergy of cross-functional teams, information flow from different departments, difficult to find experts in the field, failing to comprehend the effect of design change over all disciplines, lack of knowledge about all elements of mechatronic, low market penetration, teams structure becomes complex, ownership of individual segment, complex internal and external stakeholder dependency.

3 Proposal for an Agile Hybridization Approach

From the past few decades, the traditional approach was dominant in the mechatronic industry, but it fulfills very few of the current challenges faced in product development. Using traditional product development exclusively have advantages and disadvantages. Agility in mechatronics is beneficial to support continuous integration within the teams from different domains and reduce the lead time to introduce new product or updated versions of it [30]. But, the change could be overwhelming to transform the organizational culture from traditional to fully agile. As a result, this proposal is focused on a hybrid approach including a more agile mindset. All the criticalities have been studied and taken into consideration while preparing this hybrid agile framework. Hybrid approach can provide flexibility in designing the product along with the rigidity

in the phases of product development where changes could be costly and disrupt the timeline of project.

3.1 Requirements Derived from Criticalities

Criticalities mentioned in chapter 2.2 have been translated into requirements for building an effective product development method by following MBSE methodology. This methodology includes a black-box analysis with various views (from an external point of view) that generate all the derived requirements that the system has to fulfil. It is more described later, as it has also been used in the hybrid approach. Those requirements are as follows:

Product and development process related:

- Faster product development
- The method should be able to handle complex modelling
- To provide a well-defined and iterative way to develop product architecture
- Focused on the development of each module with iteration
- Possibility to adapt changes in product architecture and module at any point in the product development
- Suited for product customization
- Should minimize the cost of development and of the related physical prototyping
- Should follow values of agility
- Use of virtual prototyping
- Evaluation of product, based on the product requirements

Organization related:

- Efficient communication within the development team
- Well-formed cross-functional team
- Improvement in knowledge sharing capabilities between cross-functional departments
- Size of the involved team should be between 5 and 9 in one team
- Well established decision-making system to convey changes in the product requirement
- Need of involving supplier
- Regularly involving customers in the review process
- Involvement of a market research team in product development
- Simple team structure
- Single owner of the product to solve documentation in the product development management
- Effective change management

An efficient product development method for mechatronic products requires certain qualities mentioned above. Most important requirements are based on the use of iterations which can provide a better quality product. In order to create a cheaper complex product, a product development approach should consist of a state-of-the-art

virtual testing technologies and involvement of different stakeholders in it. The proposed method also demands a well-defined team structure that efficiently supports communication between internal as well as external stakeholders.

3.2 An Illustration of a Hybrid Approach: V-Model with Scrum

To illustrate the benefits of such agile hybridization, we present here an example of a way to hybridize tradition and agile approach for mechatronic products development. Due to the merits of Scrum to prioritize the backlog, iterate the development, with a full development workflow during each sprint and high compatibility with the development of product architecture and modules of product, it has been selected for this first hybrid approach. This hybrid framework consists of Scrum in the first half of the V-Model. The basic idea behind the framework is shown in Fig. 2.

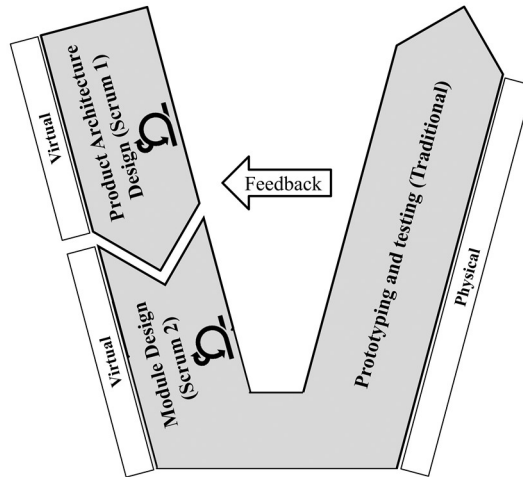


Fig. 2. Basic idea of a hybrid framework- V model with Scrum

This V-Model is divided into three phases, product architecture design, module design and prototyping along with testing. Among which, product development in the first two phases will be done in iteration using the Scrum method. The output of these first two phases will be carried as an input for the next phase once the review has been done by the team, as well as customer. Physical prototyping and testing will be done with a traditional approach as virtual product development have undergone many iterations which would resolve most of the issues with module design. This way, the cost associated with the physical prototyping can be reduced, and it also reduces the possibility of any uncertainty which might arise in the physical prototype building.

The detailed framework of V-Model with Scrum is shown in Fig. 3. As shown in the figure, the requirement gathering and analysis stage is carried out with a black-box analysis. An analysis to build the requirements by exploring all the views in agreement

with the customer is a black-box analysis [31]. This analysis aims at increasing the comprehensiveness of the product backlog and limit late costly changes. It is performed through the identification of its life cycle, system context and system-environment interaction. This analysis includes the definition of external interfaces, which are introduced as requirements and finally can define the product backlog [25]. In the traditional approach, more in-depth analysis is carried out by dealing exhaustively with all the requirements in order to avoid further changes. In the agile approach, the customer can change the requirements to be quickly taken into account.

The stage of building a product architecture goes through white-box analysis with the Scrum method. It defines the architecture of the system, starting by its functions and then logical and physical modules. At the end, product architecture is validated regarding the requirements whole set defined during the black box analysis [25].

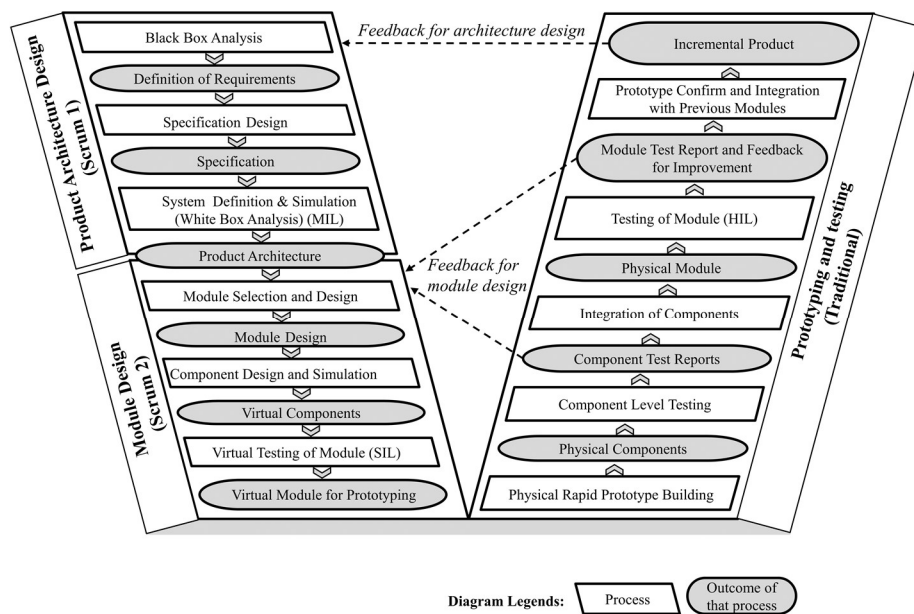


Fig. 3. Detailed hybrid framework- V model with Scrum

Then a series of N Scrum Sprints can be carried out. For each sprint, some requirements are prioritized and put in the Sprint backlog to develop a particular module allocated to a specific function. When enough virtual testing of modules has been verified, the traditional physical prototyping can then be performed.

Virtual testing has been introduced to test the module design in the second phase of this framework, as it provides flexibility to test and ask for feedback to customers in less time and with no investment in a physical prototype. At the beginning of the third phase, artifacts of this framework are referred from the conventional V-Model with few changes at the physical prototyping, testing and integration phase. The use of rapid prototyping method is highly recommended as it could provide physical components in

short duration without investing into a conventional way to produce a prototype from suppliers. The most popular rapid prototyping method is the additive manufacturing which is also known as 3D printing.

In order to test product architecture, virtual design of modules and hardware prototype, simulation techniques from a model-based design approach are used. Functions of the product are tested with model-in-loop (MIL) simulation technique and software of the respective ECU will be later checked by software-in-loop (SIL) simulation technique. In order to test each module or increment in the absence of the full product, hardware-in-loop (HIL) simulation technique is used as it can provide test results before the final assembly and flexibility to iterate the development of that particular module instantly.

A benefit of this framework is that, product architecture can be altered even after building modules also, if asked by a customer in a review at the end of the second or third phase. This framework has been built to solve the critical problems in mechatronic product development, yet with the simple use of Scrum, which makes it easy to adopt and use.

3.3 Analysis of the Adequacy of this Proposal with Respect to the Requirements

Requirements described in chapter 3.1 for the development of a hybrid approach are cross-verified with the proposal. It has been found that some of the requirements are fulfilled in the hybrid framework. Analysis of the adequacy of the hybrid approach is explained briefly below.

The framework is in compliance with the following requirements:

- Faster product development: due to the inclusion of virtual testing and rapid prototyping techniques, development time can be reduced.
- A method should be able to handle complex modelling: iterative approach of designing product architecture as well as modules (enabling architecture changes) provides an efficient way to handle complexity.
- A well-defined and iterative way to develop product architecture: the use of Scrum in the first phase to allow modification in product architecture if necessary.
- Focused on the development of each module with iteration: use of Scrum in second phase.
- Possibility to adapt changes in product architecture and module at any point in the product development: customers are involved at the end of each phase and even after testing of a physical prototype changes can be done in a product architecture.
- Should minimize the cost of development and of the related physical prototyping: the use of virtual testing and 3D printing reduces uncertainty in the prototyping phase and then the associated cost.
- Should follow values of agility: the agility values interpreted in context of hardware product development explained by [32], are fulfilled. Regarding the necessity of documentation, it is an organization's decision to define the requisite list of documents for their use.
- Use of virtual prototyping: possible at the end of the second phase.

- Involving customer in the review process: permitted at the end of each phase, and after each sprint in the first and second phase.
- Evaluation of product based on the product requirements.

Requirements not specifically addressed:

- Efficient communication within the development team.
- Well-formed cross-functional team.
- Improvement in knowledge sharing capabilities between cross-functional departments.
- Size of the involved team should be between 5 and 9 in one team and efficient team structure with decision making ability of each member.
- Involving supplier and market research team in the process.
- Suited for product customization.
- Effective change management.

Most of the essential requirements, such as the method should be flexible to adapt changes at any point, involving the customer in the development process, and an iterative method, are fulfilled. This approach will also result in the reduction of the cost and duration of the development. Use of rapid prototyping techniques and virtual commissioning have solved problems with time and cost and provided practical and easy manoeuvring while iterating the development cycle. Requirements from the organizational aspect are not completely fulfilled, they will be taken as a reference for the future development of this hybrid agile framework.

3.4 Guidelines for the Implementation and Use of Hybrid Approach

Before adopting the hybrid approach for the multidisciplinary product development, it is crucial to mention certain key structure or guidelines an organization should follow. Requirements to adopt agility, use agility, requirements or change in current product development processes and an organizational structure are mentioned in Fig.4. These requirements are extracted from literature research and interviews.

The four core values of agility have been found efficient and useful in software industry. Here, it has been explained how agile values from software industry could be adopted for multidisciplinary/ hardware product development.

- Mechatronic product development requires an effective communication channel within the involved team that consists of experts from multiple domains. Increasing complexity within a product requires complex interactions between many experts and stakeholders [32].
- Comprehensive documents which are not necessary while the development of product should be omitted except documents such as the documentation for the concept development, technical specification, drawings and interface description [32].
- Customer involvement at early stage in order to prepare a product architecture, features and interfaces is beneficial instead of a signing of a contract only and deliver the product directly [32].

- Adopting changes over following plan provides the assurance of meeting market requirements more accurately. Customer differentiation is a continuous process till the end, based on a iterative approach, allowing for the adoption of any changes to the product throughout the development process [32].

According to a four stage adoption process [33], to confirm the adoption of agility, an organization needs to assess its competency. In the pre-assessment phase, the factors which can resist this change are being identified. Those factors are: (i) no necessity of agility, (ii) lack of funds to support the adoption process, (iii) unavailability of executive support. If these factors are pre-assessed, it will save the organization's time, cost and efforts in adoption.

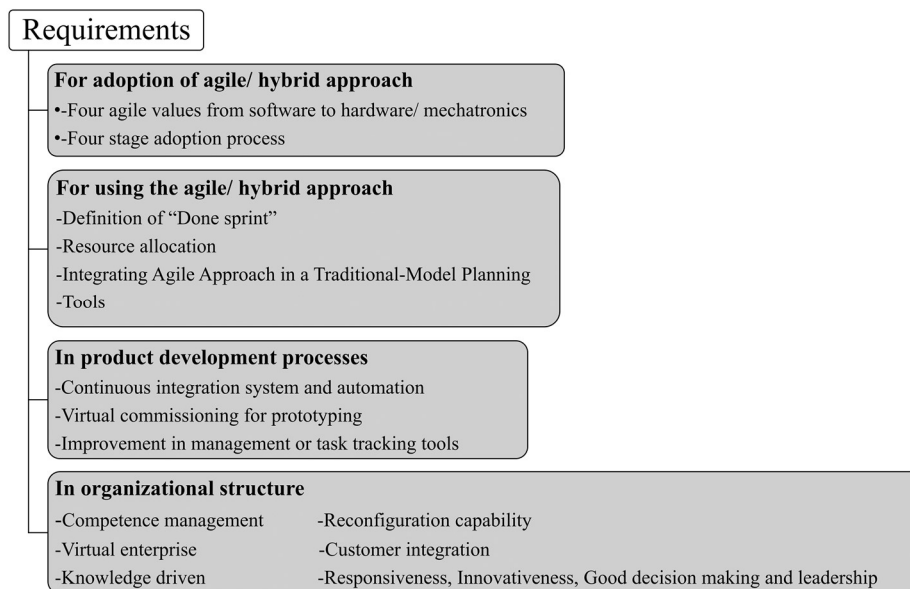


Fig. 4. Guidelines for implementation of a hybrid agile approach

Other guidelines to adopt and use agile method for mechatronic product development are as follows,

- Specify a "Done Sprint": unlike software, it is not possible every time to produce a working prototype in hardware product development. Sometimes working prototype is achieved only after the final iteration. The organization must decide what could be the outcome of each iteration in order to provide an incremental product to the customer [34].
- Resource Allocation: in the hardware product development, procurement, prototyping and testing activities which are dependent on different teams and stakeholders can have waiting times. During these waiting periods, a team can neither finish the sprint which includes prototyping nor go forward with the next sprint without the outcome of the previous sprint. Cooper et al. have provided a solution for teams to work on different tasks in the meantime [34].

- Integrating Agile Approach in a Traditional-Model Planning: coupling of traditional agile process with traditional approach can be difficult [34]. Required skillset should be generated within teams throughout the product development processes to support the agile approach adopted at one particular stage or all stages.
- Tools of agile methods: it is the responsibility of an organization to find and practice the tools which are suitable for them. With conventional methods of tracking the progress and managing the development is quite complicated and inefficient. For tracking the progress, new tools should be incorporated within the system, such as JIRA. JIRA tool helps track the tasks, make boards for Scrum and Kanban, effective communication by notification feature, project timeline, performance check of a team and report handling [35].
- A continuous integration system and automation: in order to respond faster to changes in the software product development, continuous integration of codes into the server for testing is automated. These practices can be used in mechatronic product development and system design phase [36]. In this phase of system design, the work is done daily or weekly and will continuously get updated on a virtual prototyping platform for quick feedback. This way, a team can save time by one complete iteration (sprint in case of Scrum-based development) as the small defects, which will be found in a sprint review, are surfacing while working.
- Unlike software, mechatronic product possesses substantial parts which are hard to deliver after each iteration. An author has provided an alternative to hardware prototype: the virtual prototyping. With the help of virtual prototyping, time and cost associated with incremental prototypes will be reduced [36].
- Few organizational guidelines are as follows: competence management, virtual enterprise, knowledge-driven organization, reconfiguration capability, responsiveness, innovativeness, good decision making and leadership [37].

These are the most important requirements to adopt and use in an hybrid agile approach. In order to change the organizational culture from traditional approach to agile approach or hybrid approach, organization must focus on the steps of change management which can be a topic for future work in this area.

4 Conclusion

V-Model has proven to be an efficient method in both software and mechatronic industry. Even though a product can be developed in iteration with V-Model, it was restricted and needed a full cycle to be completed before the next iteration. The proposed hybrid approach of the V-Model with Scrum for developing the product architecture and each module, has provided freedom of iterating specific phase within one cycle of V-Model. Also, the proposed approach has explained the use of a rapid prototyping technique and virtual testing to improve the efficiency of the product development method. The proposed method has addressed the most critical issue such as the need of iterations within a traditional method, need of reduction in time as well as the cost of the development process and adapting the changes gathered from the continuous customer differentiation, in the product through iterations.

Along with the hybrid approach, essential guidelines for implementing and using the hybrid agile approach are discussed. Four values of agility have guided the software product development throughout these years. Now, their interpretation for mechatronic product development will be beneficial to understand the agility for mechatronic product development. Remaining guidelines have stated the importance of the “definition of done”, resources, tools, the coupling of the two approaches and virtual prototyping.

With the use of these guidelines and the proposed method, better quality product is expected with less development time and cost, and most importantly, complying with the current market needs. Further development to the present work will deal with the application of the proposed approach to a set of industrial use-cases, in order to validate the actual results of the research. Also, presented results will be applied in a pedagogical context for the design of a mechatronic system, modular robot.

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