Requirements Engineering for the Development of Disruptive Systems Engineering Innovations

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***Abstract*—Most system development processes today are characterized by a certain flow or structure that they follow. Most of these processes begin with the definition of requirements or needs that are introduced by the stakeholders. Yet, the effects and actual satisfaction of the requirements occurs further down the line with a significant time delay. This discrepancy makes achieving the objectives of a development project difficult, which can be especially critical when it comes to products that are supposed to or have the potential to disrupt a market or sector. To address these issues, the paper at hand shows a concept based on a disruptive technology framework that ties attributes of these technologies to the requirement definition and elicitation. By connecting the potential for disruption to the requirements, instead of analyzing the circumstances retroactively, specific aspects can be evaluated regarding their impact and sensitivity. The understanding that this impact analysis yields helps to set up and guide a system development for disruption to at alleviate issues that might reduce the system's potential. The concept is shown using the example of new vaccine developments.**

Keywords—requirements, system development, requirements engineering, systems engineering, innovation, disruption

I. Introduction

The development of systems and products today is characterized and influenced by a multitude of factors that play different roles at different steps in the process. Overall, regardless of the field or area, systems and products are developed to fulfill a specific purpose or solve a certain problem [1]. To support this problem solving process and assist with the sequential steps of the development, different methodologies have emerged over time. The most popular models include, but are not limited to, the Waterfall Model [2, 3], the Stage-Gate Model [4], and the V-Model [5]. In most models the development process begins with the definition of needs and or requirements. These aspects serve as the criteria that the system in question has to fulfill with its design and are supposed to clearly define the purpose. For instance, requirements are defined in the first phases of the Waterfall Model and in the second step of the Stage-Gate Model.

Despite tried and tested approaches, such as the ones above, there still are issues and potential pitfalls when it comes to requirements. One of these issues is the fact that requirements, due to their position in the process, are defined before any actually development or design decisions have been processed. Thus, the requirements and their definition have to be considered at least in part speculative and uncertain, which is exacerbated by the fact that the multitude of factors mentioned above is subject to swift changes. These dynamics make the definition of requirements difficult. To add to this difficulty, the effects and consequences of the requirements become visible with a significant delay in the process, which makes adjustments difficult or impossible.

In addition to the described objectives, most systems and products that are produced for profit also target expansion and success in specific markets or sectors. This success is not exclusive to segments that a product has already been introduced in, but also pertains to new markets to exploit. The former position the product or system in competition with other contenders. Thus, not only the objective of the development is of relevance, but also the potential of the system in the market and compared to competitors. Extreme cases of this potential and its realization are market disruptions and innovations [6], which is what the research at hand is about. These edge cases have a lasting and disproportionate effect on and in the market as they successfully manage to capture a significant share and push competitors out of the market.

Naturally, disruptive products and systems are a desirable outcome with high potential not only for profit. Yet, also considering the dynamics explained above regarding requirements, targeting disruptive innovation is subject to an abundance of factors that are maybe impossible to consider in their totality. Thus, achieving disruption and targeting it from the requirement specification steps onward is an attractive, but complicated and possibly complex task. These difficulties and related questions are what the presented research attempts to address: how can the potential for disruption and innovation be considered at the requirement definition and elicitation so that a system development process can be guided by a specification that is most supportive regarding the disruptive potential of the resulting system/product.

The achieve this and develop the proposed concept, the work of Edwards, Nilchiani, and Ganguly [7], which was first introduced in 2019 and further expanded in 2022 [6] a was used and conceptually combined with the concepts presented by Vierlboeck, Nilchiani, Blackburn, and Dunbar [8, 9]. By using these concepts, [6, 7] for the disruptive potential and tipping points, and [8, 9] for the requirements engineering aspects, a novel concept was created that is based on a reverse-engineering approach of the discovered connections and interactions. To outline this concept, the paper at hand is divided into five sections: this first section outlines the problem at hand and sets the frame for the conducted research. The second section presents the literature and current references to put the work into perspective. Section three then outlines the concept itself and how the different aspects come together to allow for the solution of the problem stated above. Also, an example for the application is outlined. Following the description and example, section four discusses the concept and its limitations. Lastly, section five provides a conclusion and outlook how the presented work is being continued.

II. Literature Review and Foundation

Since the presented research includes two scientific fields, the literature review is split into two sections: requirements engineering and disruptive innovation.

A. Requirements Engineering

All the way back, the literature on requirements engineering (RE) dates back to 1960s [10] in Software Engineering [11]. The term 'requirements' can be found even further back in time, even before the 20th century [12]. Through time, approaches and standard have been developed for the handling and management of requirements and it can be said that requirements in the system development process have been applied for multiple decades [13].

The most notable standards for RE started to emerge in the 1990s and early 2000s, which also coincided with the inception of related journals, such as the Requirements Engineering Journal [14]. The first standards by reputable and institutions are for example the IEEE Std 830 and 1233 [15, 16]. In addition, an ISO/IEC/IEEE standard combined different existing approaches into one general standard in 2011 [17]. In said combined standard, requirements engineering is defined as "an interdisciplinary function that mediates between the domains of the acquirer and supplier to establish and maintain the requirements to be met by the system, software or service of interest" [17]. Furthermore, this comprehensive standard defines guidelines for stakeholders, formats, and even formulation. Overall, standard 29148 defines a framework for RE that furthermore also includes organizational aspects in combination with process aspects.

Standards and unifications, such as the ones outlined, were also the reason for the expansion of RE beyond its original field: Software Engineering. This expansion included fields in engineering design [18, 19], mechanical engineering [20], and management [21]. With this expansion, RE became widely adopted and can today be found in almost all fields where systems/products developed, for example, in car design [1].

In the last five years, numerous publications have emerged that address the issues between Agile and RE [22-34] since the former stands in stark contrast to the commitments that requirements are based on. Additional trends can in the directions of data analyses, the application thereof, and different algorithm and processing approaches that support the requirements engineering steps and process [24, 35-40]. Also, a trend can be seen that focuses on the security of systems as well as resilience [41-47].

The substantial history and active research described above shows that there is no shortage of insights and knowledge when it comes to RE. Yet, despite its extensive history, there are still opportunities to improve current approaches or expand into a different direction [48]. One of those directions, as currently being worked on by Vierlboeck et al. [9] is a predictive approach to requirements that allows for the assessment of requirement implications before the subsequent development steps are being conducted [8]. A predictive approach addresses various issues, such as uncertainty, as further explained in section four. The publication [9] showcased a novel RE approach that utilized NLP for structural elicitation. This approach is used in part for the concept described in this publication, starting in section three.

B. Disruptive Innovation – An overview

Disruptive innovation can be stated as a process that helps in establishing new products and/or services through initially targeting a particular market segment, and subsequently expanding to the mainstream market to eventually displace established companies and their sustaining technologies [49-51]. Products and/or services arising of disruptive innovation follows a different value network as compared to their established counterparts. The initial performance level of a disruptive product lies well below that the value network demanded by the existing customer base, and therefore are initially neglected by the mainstream customer market. However, this new product/technology attracts the attention of a different set of customers – a set that were previously either underserved or overserved in the market [49, 52-55]. With gradual advancement of time, it improves its performance to a level where the mainstream market segment finds their requirement being met by the disruptive technology. The disruptive technology, with time, finally reaches a point where it surpasses the incumbent technology, thereby facilitating the mainstream customers to switch to the new technology. As a result, the market incumbents often find themselves bereaved of customers in the long- run and no longer relevant in that market.

III. Concept and Approach

As outlined above, the presented concept utilizes the model and simulations presented by Nilchiani et al. [6, 7] as well as the approach developed by Vierlboeck et al. [9]. The referenced simulation model assesses the tipping points in relation to disruptive technologies and showcases the dynamics how technologies interact within the market. At the core of the model is a mathematical implementation of a tipping point measure for complex networks that connects with a theoretical framework for the dynamics of disruptive technologies. By using a predator-prey model, the behavior ion incumbent and entering (potentially disruptive) competitors can be modeled. Furthermore, a resilience index is included that measures the tipping point in the market, which is located where the disruptive technology overtakes the incumbent technology or technologies. Based on these dynamics, a reverse approach is presented in this paper, which will allow for a forward-looking approach instead of analysis of existing cases that lie in the past.

When looking at the model shown in [6], we can see that the approach allows for the analysis of the reliance index, which measures the success/fail probability of the technology in the given market. The success and fail probability then allow for the deduction of the possibility to push the incumbent competitors out of the market and take over. These dynamics and respective tipping point can be assessed using various factors, such as sales numbers, as demonstrated in [6], but also performance aspects.

Because of the mathematical foundation of the model in [6], a reversal of the approach allows for usage in the other direction: instead of analyzing existing data, the drivers of a desired outcome can be assessed in conjunction with the factors responsible for undesirable results to avoid. This causal chain and the respective connections are outlined in Figure 1 below and will be further explained hereinafter.

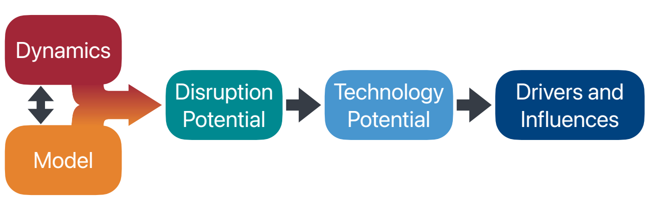

Fig. 1 Causal chain for model implementation in concept

As shown in Figure 1, the insights that the model provides regarding the dynamics of a given technology/market can be used to elicit the disruptive potential at a given state. This can be achieved through different ways, such as scenario analysis, for example. Let's assume, for instance, that a systems developer wants to assess the potential of a new product regarding its disruptive opportunities given different markets. By utilizing the simulations shown in [6] with assumed parameters and time frames, in addition to different scenarios, not only can the different markets be analyzed, but also the potential that the prospective entering technology/product might have. If then, for instance, none of the markets show an acceptable level of disruption possibilities, the technology/product might be targeting the wrong markets or is entering at the wrong time, which requires reassessment as a result. This can prevent failures or sub-par market performance and conversely show promising success opportunities. The cases studies currently being conducted will showcase these processes and the application specifically.

Adding to the potential analysis, the work by Vierlboeck et al. comes [9] into play. By combining the analysis above with the definition/structural decomposition of the requirements, not only can the disruptive potential be assessed against the market and competitors, but also the specific requirements considered. This brings together the concept of disruptive potential with the defining factors in system developments, the requirements. Thus, a reverse use of the situation enables valuable inclusion of insights during the requirement definition and elicitation; meaning, once the drivers that are connected to the market performance are identified, they can be adjusted if necessary and analyzed regarding their sensitivity to increase the disruptive potential. This means that during the decision-making process, additional information can be harnessed to provide a favorable foundation for the system development and ultimately its outcome regarding success.

The dynamics described above are a product of the loop outlined in Figure 2 below. As depicted, the main influencing factor that the entity that is developing the system has, is through the requirements. These requirements define the system that will be developed, which in turn influences and interacts with the market. Yet, there is a very important delay factor to consider since the development takes time and thus, the effect is not immediate. As a result, there is no feedback right at the definition phase, which makes consideration difficult. Yet, with the approach shown in Figure 1, the loop in Figure 2 on the right can at least be assessed and or simulated through scenarios, which allows for improvements and thus mitigation to some extent of the uncertainty.

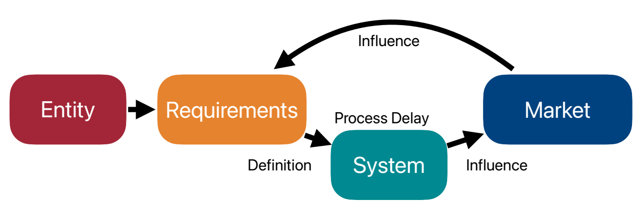

Fig. 2 Influence Loop between market, system, and Requirements

These connections and insights lead the definition of a sequence/process. With the concept based on the simulation model, the factors influencing the disruption possibilities can be assessed and scenarios considered. This allows for a certain amount of predictive power within the cycle (Figure 2) and as a result, the requirements can be adjusted/set accordingly. By using these insights during the requirement definition phase, a foundation for the development can be set. This set foundation can help to avoid potentially difficult path that reduces the chance to innovate and disrupt the market. The inclusion of the model consideration is shown in Figure 3. While the depiction might seem linear and sequential, it has to be noted that the overall process is not necessary a singular application case and can be repeated if needed or helpful.

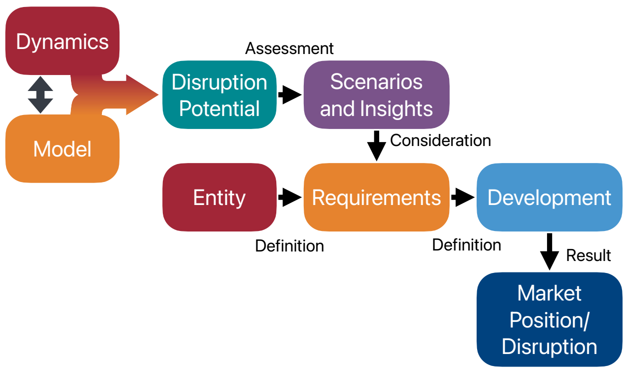

Fig. 3 Inclusion and Consideration of Model, and Disruptive Potential

As shown in Figure 3, the dynamics of the model used for scenario analysis can be considered in the requirements. For instance, if a market shows a particularly high saturation of some sort, the specifics can be analyzed and even extrapolated to allow for an assessment regrading which trajectory or product requirements yield the highest potential to stand out in this saturated environment. This can then be factored into the requirements that are defined by the developing entity. Through this consideration, the model insights shape the development and ultimately influence the resulting system. This way, the predicament of the causal loop shown in Figure 2 can be mitigated through predictive assessment.

In general terms, the process can be followed and used to adjust the requirements where necessary to align with the desired disruptive potential. For instance, if a saturated market has been identified as the target, as was the case with the camera study in [6], a technology that provides the same value or functions with little to no other benefits cannot succeed and will not catch foot in said market. This dynamic can be seen, for example with the historical case of VHS and Betamax tapes. Although Betamax was able to catch nearly the entire market initially, the longer runtime of VHS tapes lead to the eventual dominance and preeminence of the latter. Such factors, such as the runtime and current market consideration thus can and have to considered, including their sensitivity, when the requirements, such as run time for the tapes, are defined to set promising paths for the product or system.

Now, to illustrate the application and benefits of the concept above, an example shall be provided and explained. The chosen example is the development of vaccines given their recent popularity and media attention, which also correlates with other parameters, such as stock prices [56], for example. Since no numerical and quantifiable case study has been completed yet, no company names and or references are provided in this publication and instead, we discuss a theoretical case that involves three companies: company A produces traditional viral vector vaccines and is considered the incumbent technology, company B has a Messenger RNA (mRNA) vaccine that challenges the incumbent and has recently been introduced, company C is currently in the process of developing a new vaccine. The model will be demonstrated using company C.

During the requirement definition and elicitation, company C applies the approach described in this paper. Thus, in a first step, scenarios are run and the disruptive potential of the market in general is defined. These scenarios optimally cover a wide range of possibilities and compare the entering product to the incumbent ones (company A) as well as potential competitors (company B). With the insights gained from the analysis then, the overall potential for disruption can be gained. Say that there is potential for disruption and the parameters show the possibility with the given parameters, then the gained insights can be used to further assess the drivers of the possibility. This assessment can either be done through a sensitivity analysis, or by evaluating which requirements define the factors that yield the market position.

Given the example at hand, product price is most likely not a strong driver for adoption since in a vaccine market, the end consumer does most often not directly pay for the dose or the administration. On the other hand, performance, meaning the absence of side effects, for instance, can be a strong factor for success. Furthermore, other aspects, such as manufacturing and distribution flexibility can play a huge role and even time to market can be critical. Thus, the scenarios can be evaluated again given the possible changes to the requirements. Time-to-market for instance can have a huge impact on the disruptive potential, as seen in [6], and thus, evaluating different scenarios based on different requirement parameters will help find the best compromise between what is possible and the desired disruptive potential and according β_{eff} value, as shown in the simulation results in [6].

With the thoughts and steps above, the approach presented becomes an iterative tool that can not only be applied in the beginning, but even all throughout the development process repeatedly. These repetitions can also be applied in conjunction with change management and assessment, for example. Figure 4 below depicts the cycle and its information flow, which can be repeated as necessary to improve the information creation and as a result reduce uncertainty and risk. As depicted, the consideration of the outcome allows for an adjustment loop that enables a certain predictive power that was previously not possible.

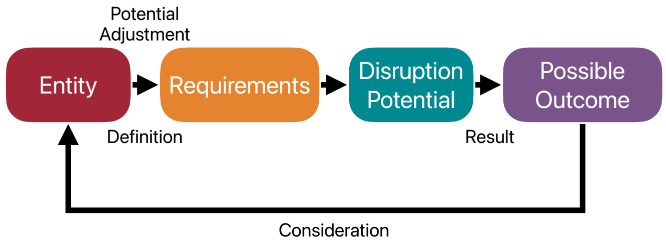

Fig. 4 Re-Consideration loop to adjust requirements

In addition to the possibilities described, the model can also consider larger and more interconnected relations between variables due to its simulation foundation. Thus, the change or adjustment of multiple requirements can be assessed simultaneously, which can reveal lateral influences that might not be directly visible or expected. Such dynamics and the potentially complex behavior that comes with them are currently being put to the test in quantification case studies.

All in all, the described concept has great potential to benefit from the simulation foundation described above to make it usable not only in hindsight, but also provide a tool for systems development processes that can be used to assess, gauge, and guide decisions right away starting early with the requirements engineering steps. Despite this potential though, there are some limitation that have to be considered, which is part of the discussion section below.

IV. Discussion

As the concept and example in the last section show, the application and benefits of the approach are manifold and can be used in more than one way. This versatility helps as well with the rigidity and risk that oftentimes is introduced with requirements. This rigidity and immutability has different consequences for different systems. For instance, when digital systems are concerned, requirements can be changed with more flexibility due to the fact that code can be adapted and changed with relatively low effort. This is also the reason for the growing application of Agile practices in the software sectors. Yet, when physical or cyber-physical systems are concerned, decisions have to be made that cannot be changed easily in the future. These decision apply for instance to prototyping, sourcing of materials, or setup of manufacturing and distribution chains. Thus, in the latter cases, when the consequences of change are more grave, the benefit of the presented approach becomes even more prevalent.

Also, the definition of requirements has been traditionally shaped by discussions and potential discord, where each shareholder or party tries to defend their interest. Here, the approach presented can help to make data-driven decisions that can be assessed irregardless of stakeholder interests in order to develop and introduce the best possible product given the desired outcome and performance in the market. Therefore, the presented research does not only contribute to the systems development and RE fields, but also to organizational aspects and management as well as business research topics.

Yet, despite the functionality and points above, there are limitations that have to be mentioned. The first limitation is a result of the potential immutability of requirements and stakeholder interest. In a closed-off environment, such as the vaccine example given above, the approach can be applied freely without restrictions. In a real-life setting though, the assumed degrees of freedom might not exist. For instance, if the development is situated within a company organization, the dynamics and lateral connections play a critical role that might dictate some if not all of the most important requirements. If the budget is fixed, for example, the possibilities for adjustments are fairly limited. This means that while functionally beneficial, the application in real-life settings might bring with it further challenges.

Also, it has to be noted that the research in its current form is based on two assumptions: 1) the assumptions underlying the model and simulations outlined in [6] and 2) the assumption that enough data and market insights are available to conduct the simulations and scenario analysis in the first place, followed by the sensitivity analysis. Since the case study presented in the original paper [6] use complete and comprehensive historical data, the results can be interpreted as retroactive and valid, which cannot be assumed for scenarios and predictions. Thus, while reducing the risk, other, albeit smaller, uncertainty factors are introduced. Furthermore, the reliance on scenarios also involves a quality dependance of the insights. Since the scenarios will be based on data points and predictive parameters, the results can only be as good as the foundation of these input parameters.

Lastly, as also seen in the original study [6], markets and players within them do not necessarily always behave linearly or predictably constant. This has to be taken into account when considering the results of the approach since unexpected and non-linear events can occur in markets that would invalidate some of the assumptions and therefore the results produced. Such events, while rare, are not impossible and can result from scientific breakthroughs all the way to unexpected competition, even externally induced disruptions are possible. Nevertheless, while difficult to account for, such events do not break the function of the approach since the assessments could be repeated with the changed data points if enough options for change are still available or feasible.

All in all, the research and approach presented show its benefits and potential despite the limitations outlined above. Given the foundation of the simulations, case studies to further illustrate and prove the function are currently being conducted and planned to be published in journals as soon as possible. We argue that the presented approach can enable significant predictive assessment benefits and we plan to extend its function further, as outlined in the conclusion below as well.

IV. Conclusion

The manuscript above described a concept that was derived from a disruptive innovation simulation [6] framework that is based on tipping point assessment to allow for the evaluation of influencing factors from the beginning of systems development onwards. By reversing the approach of the simulation and through sensitivity analyses, the factors and aspects driving innovation and disruption can be elicited and thus considered in the requirement definition phase. This allows for a more informed development process overall, especially at the requirement stage and mitigates some of the commitment issues that requirements involve.

With the presented concept, a new style of consideration of the dynamics of innovation and disruptive technologies is enabled. By factoring in the different aspect that influence disruptive and innovative potential of a technology and system, previously difficult considerations and assessments at the requirement stage are made possible. Including these factors in the requirements can ensure a more advantageous foundation for entire systems development process, despite the delay outlined in Figure 2. This advantageous position can foster the innovative potential and simultaneously increase the disruptive potential since it is directly derived from the analysis of the latter.

The presented concept is currently being assessed in case studies, which will be added upon completion, but at the current time, the concept already shows significant contribution potential even to management and decision-making research.

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