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State-of- practice survey in industry on the deployment of simulation in systems engineering

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Abstract: Model-based systems engineering (MBSE) has been proposed as an approach to manage the complexity of modern product development through the continuous use of models. The use of model simulation is a core principle of the MBSE approach. In the first stages of projects, it supports defining the expected system features, when in the later stages it estimates the dynamic behavior. Simulation is pushed to obtain results earlier and cheaper than with testing and prototyping. However, the development of simulation can be a very tedious and expensive task. The use of simulation is a specific part of an MBSE approach that is crucial in an efficient project management since it might be the source of high cost and skills needs but also a source of precious knowledge on the future system. Simulation opportunities are numerous, but the project manager must identify the more relevant for their project. This paper aims at documenting the current state of practice in industry on the usage of simulation in MBSE processes. The paper presents a survey conducted amongst French companies, on how they apply MBSE, Verification Validation & Testing VVT, and simulation. The perceived benefits and barriers, and the parameters influencing VVT strategies and the use of simulation are alternately analyzed.

Keywords: Model-based Systems engineering (MBSE), Simulation, State of practice

1. INTRODUCTION

Mastering the use of simulation tools in Systems engineering (SE) processes is a crucial subject for engineers. The digital world brings numerous advantages in terms of information management, processing, and visualization, but demands careful attention for their relevant and efficient utilization. The use of models proposed in the frame of the Model-Based Systems Engineering (MBSE) shall help to decrease project risks, shorten project, decrease development costs, and ensure higher product quality. For computer science, new design patterns and methods have been created. This has driven to develop more complex systems, often combining disparate technologies and elements (Huldt and Stenius, 2018). This computerized design has considerably evolved and has given rise to some very powerful systems engineering tools.

The potential to increase verification activities through simulation is a key point for the future of SE. For its promoters, the application of simulation techniques can significantly increase design knowledge and support Verification, Validation & Testing (VVT), and failure correction in an early product development stage. It should increase the confidence of the developers in the design and fosters the correction of intrinsic conceptual design failures that usually cause high rework costs if found during system testing (Hoppe *et al*, 2007). The combination of the simulation and verification tools should help the system designer to understand the trace results given by model checkers, ultimately enhancing the use of the formal verification method (Seidner *et al*, 2010).

A significant amount of work has been devoted to develop the modelling infrastructure so that multi-domain knowledge can be centrally managed and shared among stakeholders. However, the simulation capacity needed to experiment a full system dynamic behaviour is rarely available at companies that still often use traditional systems engineering practices (Zeigler *et al*, 2018). Many companies are still reluctant in deploying simulation benches mostly since doubts remain on the return on investment. Moreover, project leaders still have difficulties to get clear evidence on whether or not simulation is an appropriate practice in their project context.

This paper aims at clarifying the current status of Simulation and MBSE in companies and to identify the way of progress for MBSE and simulation tools, frameworks, or methodologies. The purpose of the survey was first to establish an overview of the state of practices on simulation usage in SE/MBSE. Secondly, it was to identify some barriers to MBSE/simulation fulfilment. In the remaining of the paper, the context of simulation and MBSE is presented. Then, the survey procedure is detailed, and the results are examined. A conclusion is given on the opportunities opened by the survey observations.

2. Deployment of MBSE and simulation

MBSE emerged to support the specification, analysis, design, and verification of complex systems using integrated system models with dedicated software tools (MacCalman *et al*, 2016). Companies and organizations have recognized the potential of MBSE and foresee benefits in terms of higher

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quality and shorter lead times (Huldt and Stenius, 2018). However, according to INCOSE SE Vision 2025 "MBSE has grown in popularity as a way to deal with the limitations of document-based approaches but is still in an early stage of maturity similar to the early days of CAD/CAE" (Beihoff *et al.*, 2014). This status is a result of several barriers to the transition from the traditional SE approach to MBSE. For example, there exist required changes from legacy practices relied on documentation, in organizations and their network of suppliers and clients (Friedenthal and Steiner, 2012). Other barriers are the high cost for such technical transition, the lack of strong management structures to support and guide the implementation, the lack of knowledge to integrate a model-based approach with current business processes, and a lack of available trained resources (Huldt and Stenius, 2018).

For supporters of MBSE, the superposition of modelling and simulation in systems engineering provides a prospect that is an integral part of a cost-effective process to meet user requirements and needs (Kossiakoff and Sweet, 2002). Simulation provides the system designer with a fair insight upon its behaviour, which is particularly needed in the early design phases of a complex system (Lerat and Roux, 2010). For example, analysing simulation model output results are one way a systems engineer can early verify and/or validate a system requirement (MacCalman *et al*, 2016). In many instances, the modelling, simulation, and analysis activities are interwoven, particularly during the development, verification, and validation phases (Aeronautics, 2016). Simulation techniques are also seen as an essential element for early VVT. In the context of the pilot project conducted by (Hoppe *et al*, 2007) , simulation techniques were used more intensively, trying to enhanced VVT planning and execution in the first phases of the project (Hoppe *et al*, 2007). In this study, failures and intensive VVT in the latter phases were avoided, resulting in an overall VVT cost reduction of 18%, which was found significant. Hoppe et al. also found a reduction in test redundancy and improved quality coordination with the pilot project engineering services. (Hoppe *et al*, 2007).

Despite the importance of the simulation contributions, project managers still have some hesitations when it comes to its deployment. These hesitations may be due to a lack of trust, when in some way the simulated model is seen abstract or simplistic (Schamai, 2013). In another point, the heavy deployment workload generally related to the complexity of the system as well as the cost of deployment represent obstacles that are largely based on the feelings of project managers as reflected in practice studies (Huldt and Stenius, 2018; Laing *et al.*, 2020). In this respect, the NASA standard 7009A (Aeronautics, 2016) proposes a set of questions to answer before simulation deployment. These questions are related to the pedigree (and quality) of the data used to develop the model, the uncertainty characterization of the model, and the correctness of the model implementation per their requirements/specifications.

Many parameters can be considered to assess the necessity of modelling and simulation tasks. The cost of modelling, skill availability, level of confidence in the estimation, reusability of the model, may be criteria to analyse. The presented survey aims at better understanding the way the decision of introducing simulation or not could be made.

This state of practice aims at understanding enablers and barriers to simulation utilization at various companies. It is also used to identify the primary criteria used in companies to decide when modelling and simulation effort might be made within projects.

3. CRRA Survey

3.1. Survey description

The survey was conducted during a workshop on MBSE & VV (Verification, Validation) organized by the CRRA chapter of AFIS[1] in January 2019. The workshop gathered 21 participants from France belonging to 18 different organizations from various fields. The respondents were not filtered and belong to a specific set interested in sharing knowledge and thoughts on MBSE. Among the represented organizations 60% of companies have more than 5 years' experience in setting up strong SE processes. It is also to be mentioned that 68% of participants have more than 5 years' experience in the SE field. This panel can be compared to the one used in (Vogelsang *et al.*, 2017) that gathered 20 respondents in a study on MBSE adoption. The used panel and the one from (Vogelsang *et al.*, 2017) are smaller than the one of (Huldt and Stenius, 2018) (66 respondents), but this latter study has been performed through an online questionnaire. The panel used in this work is complementary to the one of Vogelsang *et al* or Huldt and Stenius as it covers a new geographical area (e.g. France, where Vogelsang *et al* covered Germany, Huldt and Stenius covered the US and Sweden). It is also a more heterogeneous panel from the companies' domain perspective, aerospace and defence were representing more than 70% of (Huldt and Stenius, 2018) panel when 60% of (Vogelsang *et al.*, 2017) panel is from avionics or automotive industry. The panel of this study gathers companies from the electrical power management domain (16%), defence, civil nuclear industry, or oil & gas and less than 10% by domain for all remaining ones.

The objectives of the survey are triple: Analysing SE, MBSE, and Simulation practices in participants' organization; eliciting barriers and enablers for MBSE and Simulation adoption; finding the relevant criteria for Simulation deployment in projects. Participants were consulted with a questioner organized in 40 questions presented in 4 sections:

- The status of current SE and MBSE practices in companies (maturity level, challenges, expected benefits).
- The status of current practices of VVT in companies (VVT strategy, criteria for VVT deployment, practices).
- The use of computer-based simulation in companies (use, criteria for deployment, satisfaction/barriers).

[1] AFIS: French Association of Systems Engineering, https://www.afis.fr; French chapter of INCOSE, CRRA Rhône-Alps Chapter of AFIS

- The use of multi-criteria decision methods in companies.

The questions were developed in a way that cross-referenced the factors governing the practices of the VVT activities and those of simulation, for the close link that exists between the two activities.

Some questions were inspired from the survey conducted by (Huldt and Stenius, 2018) to analyse the link between the MBSE approach and simulation activities and trying to better understand the use of simulation and their impact on certain practices in SE field.

The questionnaire has been sent by email to other MBSE user community in France that permit to gather 4 more answers.

3.2. Observed MBSE practices

A set of questions explored SE and MBSE practices of participants. Maturity and experience were investigated. Then, the targeted benefits and the challenges to improve MBSE in companies were analysed. The participating organizations have various maturity level in SE, but 90% of them invest in developing their process (see Table 1).

Table 1. Maturity Level of SE process

Maturity degree of SE process in organization	Hight level	Advanced level	In development	Not formalized
Ratio %	15.00%	30.00%	45.00%	10.00%

Many companies from the panel are quite new to SE practices as 40% of respondents declare having less than 5 years of experience in SE. But a quarter are well-established companies in SE with more than 10 years of experience (see table 3). Nevertheless, interviewees were more experienced with 40% of the participants having more than 10 years of experience in SE. Even if many companies are quite new to SE, it can be observed that the huge majority implied in developing an SE approach develops an MBSE approach. Indeed 80% of companies declared using an MBSE approach (reminding that 10% do not have an identified SE process). It can be concluded that for the panel, setting up SE processes quasi implies introducing MBSE approaches in the company. This was true for experienced companies as for new users of SE that directly invest in MBSE. The participants were asked to give companies motivations in introducing MBSE with a semi directed question whose results showed an equal motivation between “improving communication among stakeholders”, “increasing ability to manage system complexity” and “improving quality and knowledge management” (30% of participants). Complementary shared motivations were “providing customer support” (10%), “accelerating the project” (10%).

The participant companies have difficulties to master the MBSE deployment since most interviewees (70%) indicated that the level of maturity of their MBSE process was in development or not formalized. Only 15% of companies are confident in the maturity of their MBSE process. The exploration of companies’ MBSE practices has been ended by the search of the perceived challenges to improve MBSE. Figure 1 shows the results. The main mentioned challenges are, the difficulties of integrating the MBSE with other existing processes according to 83% of participants, the need to improve skills according to 74% of participants, as well as the way tools are used according to 52% of participants. Many organizational challenges were also pointed out as formalizing the processes, creating a new structure for the management of MBSE, or having a good sponsor in the company organization.

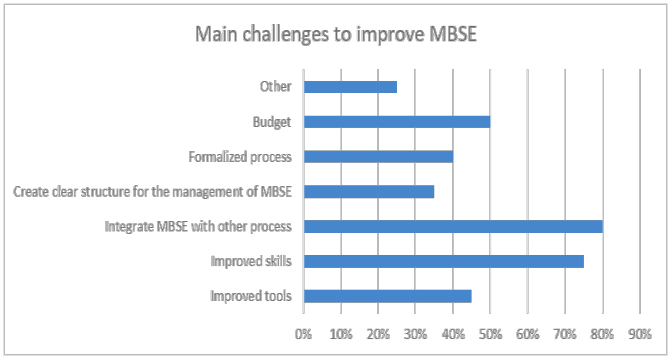

Fig. 1. Main perceived Challenges to improve MBSE

It could be analysed that a lot of challenges are due to the novelty of MBSE approaches for the company of the survey panel. Even if the MBSE principles are now developed for years, it is a very topical subject for companies interested in adopting structured SE. Our panel covers a broad scope of industrial domains, it confirms that MBSE raises a lot of interest but imposes important changes in companies’ structures. It changes the development of software frameworks, knowledge management, the skills needed in projects, the relation with clients, the project management… Many participants felt they need strong top management support for deploying MBSE since working standards changes and consequent budget is needed.

The next set of questions examined the VVT practices deployed in companies since it is a key stage of SE processes when simulation may play an important part.

3.3. Observed VVT practices

To address VVT practices, participants were invited to answer questions related to various aspects (the state of VVT practices; the considered criteria to perform a VVT action; the important phases of the system life cycle for the VVT; early VVT constraints; VVT & Simulation link).

VVT strategies are correctly implemented in most organizations. 80% of participants report having a clear vision of the VVT strategy of their organizations.

Simulation possibilities give the opportunity to make early VVT actions. To understand the importance of early VVT in companies’ strategy, few questions addressed this topic. It appears that 58% of respondents mention that their organization perform early VVT. This rate is quite modest when compared to the importance and expected benefits of early VVT as it was shown in (Laing *et al.*, 2020). To corroborate this, a high majority of participants (80%) claim that VVT activities must be realized even earlier than in their

current practices. The early VVT actions use in companies concern defining stakeholders' needs and system requirements phases (see Figure 2).

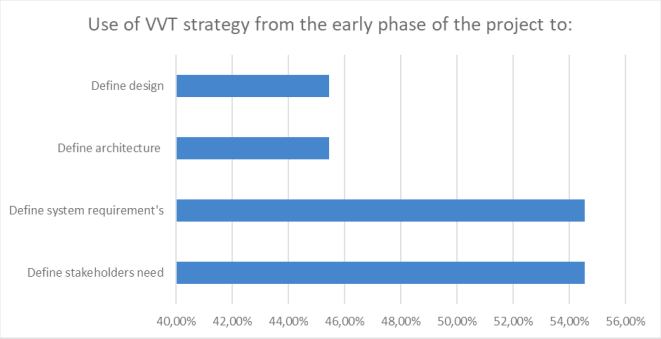

Fig. 2. Main phases for the use of an early VVT strategy in a project

The obtained results reveal the relevance of addressing new techniques to support the early VVT deployment. To succeed in such an approach, the panel were questioned on the main impediments to early VVT. According to the participants time and cost (according to 33% of participants), and technical resources availability (according to 20% of participants) are the main barriers (See Table 2).

Table 2. Important criteria to consider when deciding to perform a VVT action

To what extent the criteria below are important to consider when deciding to perform a VVT action				
-	High Consideration	To some extent	To a small extent	Not at all
Importance of verified/tested requirements	75%	25%	5%	0%
Maturity of verified/tested requirements	30%	45%	10%	5%
Complexity of system/behavior/environment to be verified/tested	50%	35%	15%	0%
Reachable result accuracy	30%	35%	15%	5%
Reachable results confidence	55%	15%	15%	5%
Benefits of detecting errors	40%	45%	5%	0%
Impact of undetected errors	55%	20%	15%	0%
Cost of VVT actions	25%	35%	30%	0%
Duration of VVT actions	10%	35%	35%	0%
Available skills	10%	25%	35%	20%
Project lifecycle phase	30%	30%	20%	0%

When moving to questions related to VVT activities it was noted that although cost and time criteria are a direct cause of avoidance/deletion or limitation of VVT actions for more than 50% of the participant, they are not the most considered when making decisions regarding the deployment of VVT activities (see Table 2). Indeed, it is less quoted than the importance of the reviewed/tested requirements (Highly considered for 75% of participants), the complexity of the system, its behaviour or its environment (Highly considered for 58% of participants), and the incidence of undetected errors (Highly regarded for 54% of participants) (see Table 2). The decision to perform or not VVT actions are related to the assessment of the benefits that these actions will bring, and the risks taken in the opposite case, as reported by 70% of participants. They claim doing this assessment within their organization and mainly considering the following criteria (see Table 2).

- The importance of the requirements verified/tested
- The complexity of the system to be checked or tested for its behaviour or the environment in which it operates
- The impact of undetected errors
- The reachable results confidence
- The benefits of detecting errors

It may be observed that the functional architecture design and system requirements analysis phases are seen as the most critical phases for VVT activities according to the vast majority of participants (see Figure 3). This information highlights the need to better integrate verification and validation activities in MBSE.

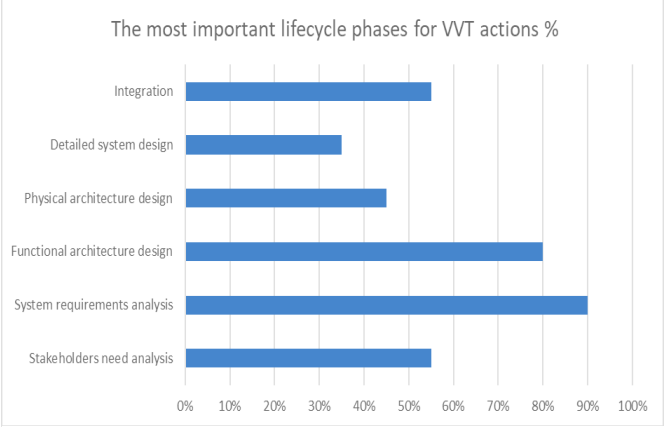

Fig. 3. Most important lifecycle phases to consider for VVT actions

Concerning the link between VVT activities and simulation, most of respondents (75%) affirms using this latter as a support to verification, validation, and testing activities. The next set of questions examined the deployment of simulation in companies and their impact on several aspects of organizations' activities.

3.4. Observed simulation practices

3.4.1. State of practice in simulation

The first set of questions of this section were analysing the current state of practice in simulation. Firstly, simulation asserts its position as a support for system validation action. When addressing the objectives of the use of simulation in the organizations today, it appears that simulation is used mainly for more than 60% of participants in system-level verification and validation. Meanwhile, the deployment of simulation is mainly related to the organization's field. As

reported by more than 50% of participants, simulation is commonly used in software and mechanical domains.

The aim of the simulation is generally to assess the performance of the systems for more than 60% of the participants, and for more than 40% for the consistency check (to determine whether there are any internal conflicts in the data), and the reliability of the state of the system.

The impact of simulation on the effectiveness of system architecture and design, requirements analysis, technical reviews, and system verification and validation is particularly important (see Table 3).

Table 3. Simulation efficiency impact

To what extent has simulation increased the efficiency to perform						
	Big Improvement	Some improvement	No change	Some impairment	Big impairment	Not applicable
Architecture and design	41,18%	35,29%	5,88%	0%	0%	23,53 %
Requirement analysis	35,29%	29,41%	11,76%	0%	0%	29,41 %
Architectural view	11,76%	29,41%	35,29%	0%	0%	23,53 %
Traceability between systems requirements and the realization	17,65%	23,53%	35,29%	0%	0%	29,41 %
Technical reviews	47,06%	17,65%	5,88%	5,88 %	0%	23,53 %
Verification and Validation	41,18%	35,29%	0%	0%	0%	23,53 %

The next set of questions focuses on the importance of simulation in projects and its impact on overall project aspects.

3.4.2. Analysis of the importance of simulation in projects

The participants were invited to complete their answers on the use of simulation by discussing how they perceive the efficiency of simulation in the project and how the deployment of simulation is decided.

Firstly, 95% of participants feel that simulation increase the quality of the tests and delivered projects. No impairment has been noted. and 5% see no changes in test quality. This result clearly shows the very high trust placed by participants in the utilization of simulation techniques to delivered high-quality projects. Nevertheless, it is not sufficient to justify full investment in simulation technologies. According to participants, an improvement in the performance and quality of certain practices has been observed thanks to the use of simulation (see Table 4 & 5). It is broadly shared for architecture and design, requirements analysis, verification and validation, and technical reviews. We observe when analysing these results that simulation is largely recognized to be useful for technical activities (design, requirement analysis, V&V, technical review). But when moving to activities aiming at consolidating the system-level view as the architectural view or traceability tasks, the participants have heterogeneous opinions. It may be concluded that simulation is seen as a strong support to enhance the quality of the system development. But it is currently not seen by most of the actors as an obvious support to system-level analysis.

Table 4. Quality improvement of the activities observed in organizations when using simulation

To what extent has simulation increased the quality of						
	Big Improvement	Some improvement	No change	Some impairment	Big impairment	Not applicable
Architecture and design	33%	43%	5%	0%	0%	19%
Requirement analysis	38%	33%	5%	0%	0%	24%
Verification and Validation	24%	33%	10%	0%	0%	19%
Architectural view	19%	14%	29%	5%	0%	24%
Traceability between systems requirements and the realization	19%	24%	14%	5%	0%	24%
Technical reviews	33%	43%	0%	0%	0%	14%

Table 5. Performance improvement of the activities observed in organizations when using simulation

To what extent has simulation improved the performance of						
	Big Improvement	Some improvement	No change	Some impairment	Big impairment	Not applicable
Architecture and design	39%	33%	6%	0%	0%	22%
Requirement analysis	33%	28%	11%	0%	0%	28%
Verification and Validation	11%	28%	33%	0%	0%	22%
Architectural view	17%	22%	33%	0%	0%	28%
Traceability between systems requirements and the realization	44%	17%	6%	6%	0%	22%
Technical reviews	39%	33%	0%	0%	0%	22%

In addition to these questions, 73% of participants judged that simulation is increasing the communication and information exchange within the project. It is also appreciated for the help in anticipating system failures (73%). Finally, 66% claimed that the use of simulation facilitates the integration of the system.

Despite the high trust in simulation utility in many project phases, many impediments to the use of simulation were revealed with an open question. 40% of respondents mentioned that the use of simulation is costly and demands highly skilled persons. 22% of respondents mentioned a difficulty to cope with model complexity. On the impact of simulation on the overall cost of the project, opinions differ, suggesting that it may depend on the type and complexity of projects. The results in Table 6 mainly suggest that it is very

difficult for practitioners to have a clear understanding on the impact of simulation on the project cost. Thus, uncertainty on the simulation ROI is an important barrier to convince managers in investing in these technologies.

Table 6. Impact of simulation on the project cost

Evaluate the impact of simulation on the global cost of SE/MBSE project	Increase the global cost (+ +)	Increase the global cost (+)	No impact	Decrease the global cost (-)	Decrease the global cost (- -)
Ratio %	18%	24%	12%	35%	12%

As a short sum up, it could be noted that the benefits of using simulation are recognized but the financial impact of its use is uncertain. To better understand how simulation deployment is decided in companies, participants were asked on the criteria utilized to make such decisions (Fig. 4). The use of simulation is then driven by the costs and the perceived complexity of the project. And by the perceived cost and duration of the VVT actions. It is interesting to observe that the decision is to be made with criteria that companies have difficulties to master (cost impact). Moreover, it can be observed that the criteria pushed by NASA (Aeronautics, 2016) to analyse simulation needs (e.g. reachable result accuracy and confidence) are among the least cited by participants. Many additional concerns are to be considered in the deployment of simulation as the potential avoidance of errors, project characteristics as available skills or lifecycle phases. This result demonstrates that the decision to deploy simulation in a project is multi-criteria and hard to clearly answer.

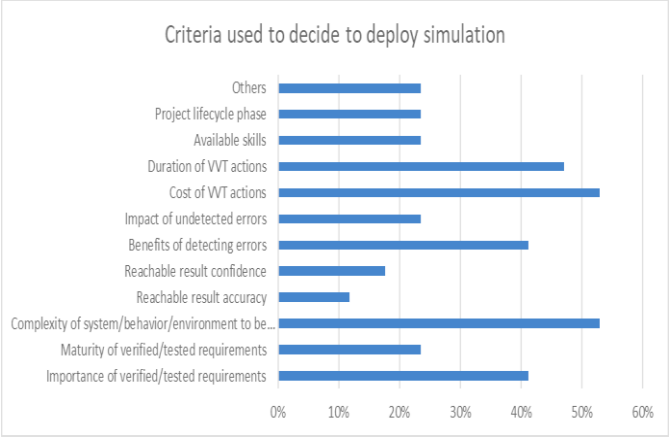

Fig. 4. Criteria to decide simulation use

4. Conclusion and Discussion

The results of the CRRA survey have shown a need for further development in MBSE for a best integration with the existing SE process and a need to further improve skills in SE and modelling activities. The performed survey points out that simulation is perceived to increase the quality of tests performed and delivered projects, it is also considered as a key element for VVT strategies. According to respondents, an improvement in the quality of certain practices has been observed following the use of simulation, mainly in architecture and design, requirements analysis, and verification and validation. Nevertheless, it is very difficult for practitioners to have a clear understanding on the impact of simulation on the project cost. The studies revealed that the return on investment of such practice must be proven to convince managers on their potential benefits. Moreover, it is admitted that actions are to be taken to master the MBSE and simulation deployment costs. These let us think that further developments to tackle these two activities during the first phases of deployment of MBSE and simulation in new organizations is needed.

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