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Published in:
CIRP Journal of Manufacturing Science and Technology

DOI (link to publication from Publisher):
10.1016/j.cirpj.2023.06.002

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

CIRP Journal of Manufacturing Science and Technology 45 (2023) 125–137

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: www.elsevier.com/locate/cirpj

Full-length article

Managing agile ramp-up projects in manufacturing – Status quo and recommendations

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Ramp-up
Projects
Agile manufacturing
Collaboration
Continuous improvement
Survey

ABSTRACT

In an ever-changing business environment, frequent new product development projects are inevitable. Ramp-up as a critical lifecycle phase plays a major role in successful product marketing. This paper provides an updated overview of ramp-up concepts, challenges, and strategies, and makes recommendations for managing ramp-up projects. To this end, theoretical insights from the literature provided valuable insights which were extended by the findings of an empirical study. The study consists of a survey conducted between November 2021 and January 2022 in 147 companies from the manufacturing sector. The paper culminates in a set of recommendations to support ramp-up projects, which are structured in three steps: preparation, conducting ramp-up, and transfer to production. The following principles have been identified as highly important in ramp-up projects, namely, agility principles, collaboration and integration, and system robustness and continuous improvement. The recommendations support agile ramp-up management and are designed to help practitioners to deal with frequent ramp-ups in a more effective and structured manner.

Introduction

Recent technological advances and global situations such as pandemics exposed the need to review agility and resilience drivers [1,16,29,48,50,59]. Meeting stakeholders' requirements and the capacity to proactively adapt to change are among the most important features of agile manufacturing. Agility in manufacturing can be defined as the ability of businesses to respond quickly and effectively to changes in market demand so as to meet diverse customer requirements in terms of price, specifications, quality, quantity, and delivery [10,45]. Implementing agility in manufacturing involves a variety of approaches, methods, and tools spanning the lifecycle of the product or service [10,11,28,45]. Ramp-up is a key phase in the product lifecycle and plays a major role in reinforcing companies' agility [4,9]. Ramp-up is a value creation phase that begins with the completion of a product design and ends with maximum production capacity. Previous research has underscored the challenging task of managing ramp-up [50,6,8]. This is due to inherent ramp-up complexity related to high uncertainty and lack of process maturity and required skills, to name just a few of the issues. Ramp-up management is also challenging as it involves other business and operational objectives beyond volume, such as time, cost, and quality [19]. Furthermore, ramp-up in the context of low-volume production settings (e.g., with high levels of product variety and customization) is more focused on productivity and quality targets than volume [34]. Ramp-up projects also involve several stakeholders from different backgrounds and various departments, as well as companies [6,49].

The ramp-up literature has received a great deal of attention over the last decade [54,55,50,39], with particular focus on conceptualization of the ramp-up phase [17,50,8] and on decision-supporting models to improve ramp-up management at shop floor level [23,27,53,20] or at strategic and tactical levels [51,41,30,6,33]. These contributions have provided the foundations for further research to improve ramp-up performance, mainly from cost and time-related perspectives. However, most of the research issues are addressed separately, e.g., product change management during ramp-up [51], capacity planning [30], learning effects [39,20], with no clear roadmap of the overall ramp-up project. This is a major challenge since, in practice, decision-makers are expected to design actions that take different facets of the ramp-up issue into consideration simultaneously, such as capacity, teams, performance, etc. Furthermore, in uncertain demand and supply situations, the need for multiple and rapid ramp-up projects can obviously be found in a

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https://doi.org/10.1016/j.cirpj.2023.06.002

variety of interrelated sectors, ranging from pharmaceuticals and healthcare equipment to consumer goods, etc. However, most of the existing research on ramp-up management is limited to specific manufacturing sectors such as microelectronics and the automotive industry [55]. It is therefore important to enhance ramp-up management through proper operational guidance, facilitating multiple and speedy ramp-up in different manufacturing sectors.

A holistic approach that helps decision-makers decide where to start and how to proceed with ramp-up projects appears necessary to tackle the issues [17,50,52]. Such an approach should provide a common basis for practitioners across multiple industries to manage ramp-up projects, while helping to tailor guidance to industry-specific requirements.

In view of these requirements, this paper provides an updated overview of ramp-up concepts, challenges, and strategies, drawing recommendations for ramp-up project management. To this end, theoretical insights from the literature provided valuable insights which were then extended by the results of an empirical study. The study in question involved a survey conducted between November 2021 and January 2022 in 147 companies from the manufacturing sector. The paper culminates in a set of recommendations to support ramp-up projects, structured around three steps: preparation, conducting ramp-up, and transfer to production. The following principles were identified as essential to ramp-up projects: first, agility principles, second, collaboration and integration, and third, system robustness and continuous improvement. The recommendations supporting agile ramp-up management can help practitioners to deal with frequent ramp-ups in a more effective and structured manner. The remainder of the paper is organized as follows: Section 2 provides an overview of ramp-up concepts, challenges, strategies, and methods. Section 3 sets out the research methodology. Section 4 reports on an analysis of the survey results and identifies recommendations for managing ramp-up projects. Section 5 discusses the principles that can increase the chances of ramp-up project success. Section 6 discusses the results and outlines potential research avenues. The paper ends with a brief conclusion in Section 7.

Background literature

Ramp-up overview

Ramp-up as a value-creation phase starts with the completion of both product and process design and ends with the transition to series production [50]. Ramp-up may also occur when demand exceeds production capacity [55]. Ramp-up allows production to switch from development on a small laboratory-like scale into high-volume-production setting [56]. From a product perspective, ramp-up is comprised of pre-series production (i.e., the first production of a large number of prototypes), zero-series output (i.e., the first production phase under serial conditions), and finally the start of production. From a process perspective, ramp-up is defined by the commissioning (i.e., functions of the production assets with the entire system approved or corrected if necessary) and the ramping up of the production phase when the production system passes from the realization to the use phase, with output volume increased to the final production level [50].

Ramp-up is strongly linked to the introduction of a new product or product variant and its related manufacturing processes. However, there are exceptions to this general definition, as new product introduction projects do not exclusively refer to completely new products, and ramp-up can also involve changes to existing models [49,55]. Thus, the inherent difficulty of the ramp-up process is often dependent on whether new, modified, or existing products are introduced and whether new, modified, or existing production resources are involved [7].

In line with the previous literature [55,21], Riffi-Maher and Medini [49] argued that given its temporary status, ramp-up is characterized by a low initial level of knowledge about the product and the process, low production output and production capacity, and higher cycle times, leading to a lack of planning reliability and frequent disturbances in processes and supply chains. Consequently, the introduction of a new product or process also implies the need for training and learning by the workforce. Ramp-up management comes into play at this point by smoothing production flows based on continuous learning and improvement [24,39].

Ramp-up management decisions affect and are affected by capacity scheduling**,** costs, and learning effects in particular [38,39,50,55]. At the start of and during the ramp-up process, capacity is typically limited, and the need is to gradually raise it. However, the capacity evolution necessitates investment decisions. The production ramp-up phase may suffer from the trade-off between a short-term capacity opportunity cost and the long-term value of learning [55]. Thus, a cost-benefit analysis is needed to support investment decisions and to stabilize and optimize production ramp-up [8,43]. Ramp-up is supported by management strategies and methods, and is challenged by the variety and complexity of products and production systems [49]. Management strategies are expected to improve the efficiency and effectiveness of ramp-up and, ultimately, enterprise agility [18,4,52-54]. Operational methods support decision-making through simulation and mathematical models to hone and select strategies [20,27,53]. Based on this overview, the next sections focus specifically on the challenges and strategies of ramp-up and the operational methods implemented.

Ramp-up challenges

Market volatility and shorter product lifecycles have led to more frequent product development and ramp-up projects [6]. The need for ramp-up increases when manufacturing systems have to be continuously reconfigured to match new market or demand situations [3,36]. Identifying and addressing ramp-up challenges is thus more important than ever.

During ramp-up, several goals need to be concurrently met, such as target output volume, quality, speed, and cost-efficiency. However, attaining these objectives is challenged by uncertainty related to external factors, such as market volatility, shorter product lifecycles, and internal factors such as low process maturity, lack of knowledge, complexity, and lack of internal and external coordination [14,25,54,55,8,27,44,22]. The ramp-up phase is characterized by low production rates, machine breakdowns, slow set-ups, defective items, and quality issues, as well as imperfect production processes partly due to production delays [27]. These factors concurrently lead to limited capacity and unstable processes. Given the potential growth in demand, this is liable to disrupt the successful introduction of production onto the market.

Learning plays an important role in ramp-up due to the lack of process maturity and the knowledge and know-how required [30,39]. However, the learning process also has to deal with the huge increase in product variety, which generates high operational complexity [44,54]. This is partly due to the lack of overview of previous ramp-up projects [14]. New approaches to knowledge and skills transfer are therefore needed to improve the ramp-up projects' chances of success [39,60]. In this vein, Letmathe and Rößler [38] explored spillover learning in the context of production ramp-up, noting the potential of studying spillover learning effects across several ramp-up projects. Spillover learning is defined as *organizational learning through knowledge spillovers.* Knowledge spillover refers to the creation of new knowledge that can be used by other parties [38]. The authors argued that spillover learning has the potential to improve ramp-up performance. In line with previous

Table 1
Ramp-up strategies according to Schuh et al. [52].

Ramp-up strategy	Aim	Suits
Slow motion	Parallel ramp-up of several variants at a constant and low volume level until all processes are verified.	Highly automated processes
Dedication	Ramp-up of all different variants with accumulative volumes and a grouped launch. Elimination of problems at an early stage.	High product variety and high logistic capability
Step-by-step	Sequential ramp-up of consecutive variants with high complexity.	High technical complexity

research [37], they empirically showed in a more recent study how knowledge is transferred in consecutive ramp-ups through observation and imitation. Most importantly, the laboratory experiment used by the authors showed that learning spills over between ramp-ups [39].

The high disturbance observed in production processes and supply chains also requires close collaboration with suppliers to ensure successful ramp-up [26,49,5,55,8]. Lack of supplier implication is a serious issue since suppliers are one of the critical factors affecting ramp-up in both the pre- and the post-phases [8,22]. Consequently, it seems natural to ensure supplier integration in ramp-up planning and management. Internal (among departments and services) and external (with the supply network actors) coordination is a key to successful ramp-up projects. From a technical perspective, the information system is just as important in the ramp-up phase. For instance, ramp-up occurs at the interface between systems for managing product data and lifecycles, such as product data management (PDM) and Product Lifecycle Management (PLM), and systems for managing production data such as Enterprise Resource Planning (ERP) and Manufacturing Execution Systems (MES). In these systems, models are interpreted differently, and data is rarely automated [55].

With the combined effect of lack of process maturity, capacity and cost issues, and integration and collaboration requirements, and in line with the idea of learning spillover across ramp-ups [39], it is clear that there is a need to capitalize on across ramp-up projects in order to continuously learn and improve ramp-up performance [24].

Strategies and methods

Ramp-up is inherently complex due to the high underlying uncertainty which leads to more frequent discrepancies between products, more disturbances within the process, and more challenging forecasting [50,54,55]. Robust strategies therefore need to be identified and fine-tuned to manage the ramp-up phase.

Riffi-Maher and Medini [49] conducted a review of ramp-up strategies and reported on a few of the most widely discussed and adopted ones. One of the first studies was conducted by Clark and Fujimoto [18] in the automotive sector, where strategies were developed based on workforce policies, learning curves, and operation patterns. This resulted in “step-by-step” strategies, providing greater stability and control of work assignments and “shut down”, reducing complexity, but potentially posing a problem for work stability and continuity [52]. Schuh et al. [52] introduced three ramp-up strategies driven by product variety, namely, “slow motion”, “dedication”, and “step-by-step”. “Slow motion” implies simultaneously ramping-up diverse variants, with constant low volumes at the beginning until the processes are verified. It is therefore suitable for highly automated contexts. “Dedication” is suitable for high product variety and consists of ramping-up all the variants with accumulative volumes and a grouped launch. “Step-by-step” corresponds to a high complexity context, which involves consecutively ramping up variants with high complexity (see Table 1) [8,55]. While these strategies give general insights into how to proceed with ramp-up in a multi-variant context, they do not provide operational guidance on how to plan and conduct ramp-up projects.

Slamanig and Winkler [54] explored ramp-up strategies in the era of mass customization. To overcome the challenges of ramp-up, they proposed two strategies: a High-Volume-Low-Mix (HVLM) strategy and a Low-Volume-High-Mix (LVHM) strategy. The choice of ramp-up strategy is determined by the situation in which the product introduction is made. Medini et al. [44] explained the selection process via a simulation-based approach in the furniture sector. Becker et al. [6] proposed a mixed model for strategic production planning during ramp-up, taking net present value into consideration. Production is planned according to a time-dependent ramp-up function, taking different ramp-up curves into account. The authors used a case from the automotive sector to compare the approach introduced, consisting of strategic ramp-up planning (after strategic network planning) or sequential planning approaches. They found that strategic ramp-up planning outperformed traditional approaches. Hansen and Grunow [30] introduced a quantitative approach to plan capacity during production ramp-up, considering cumulative production volumes rather than time dependent ramp-up curves. They used linear programming to model the problem which aimed to maximise gross revenue in each market and to reduce costs, including that of constructing new production lines, demonstrating the relevance of production volume to estimate effective capacity through a case study in the pharmaceutical industry.

Ramp-up strategies need to be backed up with resources including practices, methods, and tools in order to effectively plan and implement ramp-up projects. Colledani et al. [19] stressed the importance of adapting production quality methods to accommodate disturbances occurring in ramp-up. Delayed system fine tuning to the ramp-up phase is one of the practices that shorten ramp-up duration. However, it also involves challenges linked to timeframe and budget [19]. Simulation and decision support systems are among the solutions that can be applied to predict expected ramp-up profiles and limited time and budget issues. In line with this, Klocke et al. [35] used hybrid simulation (discrete event and continuous simulation) to predict ramp-up performance. The literature also notes the role of skills transfer and knowledge management generally to improve ramp-up performance [15,39,58,60]. Some specific guidance to enhance learning knowledge transfer can be found in Letmathe et al. [37]. From a methodological point of view, the literature increasingly emphasizes the role of implementing agility in ramp-up projects [9,50]. In effect, managing projects with agility is especially useful given the uncertainty underpinning ramp-up. According to the findings from an empirical study conducted by Schmitt et al. [50], agile ramp-up has the potential to limit ramp-up failure risks. Following this idea, Bergs et al. [9] introduced an iterative product development approach to address uncertainty and stabilize and optimize production ramp-up. An important principle of this approach is the overlap between design and production. This is consistent with the idea of delayed system design finalisation [19]. Agility in this context is seen as an alternative to simulation approaches, as in the work of Klocke et al. [35]. The potential of agility is also linked to its role in enhancing customer integration and cutting ramp-up time [9,50]. With the advent of Industry 4.0 design principles and technologies, recent research has emphasized the benefits of the synergetic development of agility and Industry 4.0 [40,50]. For instance, increasingly available (big) data, smart

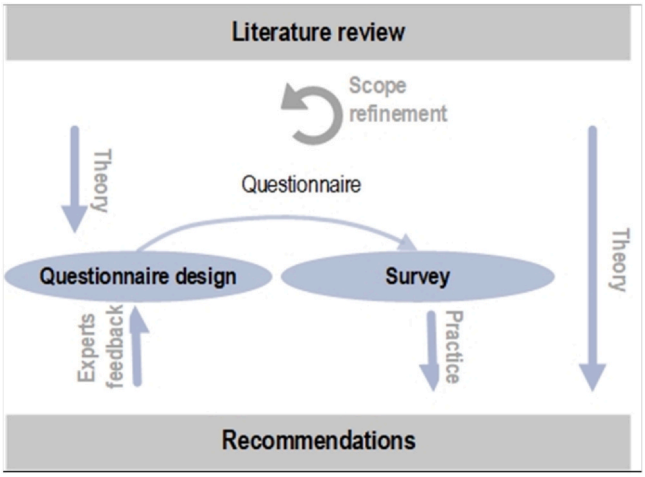

Fig. 1. Research design.

products and services, automated processes, and the incorporation of digital and physical worlds have unlocked strong potential for enhanced agility and resilience. However, this also implies major changes in the skills required to deal with ramp-up projects [50].

Overall, the diversity of strategies and methods requires guidance through a general roadmap that provides the basis for honing the ramp-up strategy and method selection.

Research methodology

In the previous section, we investigated some key contextual challenges that put more pressure on ramp-up management projects and delineated ramp-up scope, challenges, strategies, and methods. This gave us a reasonable foundation for conducting a survey-based field study [47]. To this end, a questionnaire was designed following the rational method, which is useful when the constructs of interest are not to be explored in great depth [47] (Fig. 1).

The first step of the questionnaire design was based on the general insights from the literature review on ramp-up challenges and strategies. The literature allowed us to identify some of the most relevant topics that need to be addressed to improve ramp-up performance. These were used as the starting point to define the questionnaire items. The second and third steps were conducted iteratively and consisted of honing items and scale on the one hand, and asking selected experts to evaluate the questionnaire on the other.

For the evaluation, semi-structured interviews were organized to check the relevance of the questions and ensure that the questionnaire was comprehensive and the questions clear. Two practitioners from the manufacturing sector were identified as appropriate respondents. The first is an expert and director in a competitiveness industrial cluster, in other words, a group of companies, research laboratories, and education centres supported by public funds that work to improve the competitiveness of manufacturing companies. As well as being CEO of a manufacturing company, the expert is highly familiar with today's business challenges and is also very knowledgeable about industrial practices. The second respondent is a senior engineer with considerable experience in R&D and consulting in areas such as additive manufacturing and process scaling-up. He belongs to a consultancies and aftersales department, and consequently works with several manufacturing companies. Each of the interviews lasted around one hour, giving us insights into the clarity and relevance of the questions and ensuring that the questionnaire addressed all the main points. This resulted in the questionnaire shown in Table 2.

The survey was administered online between November 2021 and January 2022 using the paid version of *SurveyMonkey*. A test was conducted in the first week after the survey was administered, the answers collected during this period were included in the results. During the study period, the questionnaire was sent to practitioners in the fields of product development, production, and operations management. These professionals were from Small and Medium-Sized Enterprises (SMEs) and large companies. The survey was conducted in close collaboration with a company specialized in survey administration and management, which helped to collect 232 answers by the end of January 2022. 78 of these were incomplete and 6 were completed too fast and were therefore removed. This process resulted in 147 complete and exploitable answers.

Practitioners' insights into challenges, strategies, and methods

Respondents overview

The respondents were evenly distributed between SMEs (48.3 %) and large companies (51.7 %), which is representative of the identified respondents' sample (Fig. 2a). 44 % of the respondents were equipment providers and mechanical engineering companies, followed by firms in the metal, food, and textile industries. 7 % of the respondents were from the pharmaceutical industry (Fig. 2b).

Moreover, several product lifetime ranges are covered by the companies in the sample. Their scores were between 17 % for products with an average lifetime of less than 1 year and 35 % for products with an average lifetime of more than 10 years (Fig. 3a). This also reinforces the representativeness of the sample considered.

Almost three quarters of the respondents are involved in NPD projects at least once every two years and 46.3 % manage at least one project a year (Fig. 3b). This provides a good foundation for further analysis since ramp-up is closely related to NPD, although it may also occur when experiencing an unexpected demand increase of existing products or services. In fact, 98 % of the responding companies have experienced ramp-up situations either in the framework of NPD development (43 %) or when facing demand turbulence (55 %). More than half of these companies conduct ramp-up projects internally (Fig. 3c). The outsourcing rate is lower in large companies than SMEs, which is unsurprising given the availability of resource across these companies' subsidiaries. Overall, having survey respondents who manage ramp-up internally helped us to gain more evidence-based insights.

Ramp-up challenges

The survey results clearly show that ramp-up is challenging for most of the companies (Fig. 4). Interestingly, according to the respondents, quality is the most critical aspect they need to address during ramp-up. 23 % of the responses mentioned quality issues as the main concern for decision-makers. This could be partly explained by the lack of process maturity and poor coordination of design and ramp-up projects, two factors that are likely to lead to a mismatch between the designed system and the actual system involved in the ramp-up.

Unsurprisingly, time and cost were among the main concerns for decision-makers when it comes to ramp-up projects, with respectively 18 % and 17 % of the issues raised. This can be partly explained by governance and project management problems and intrinsic ramp-up issues. There appears to be a general underestimation of the resources required to tackle ramp-up issues among the respondents. The lack of resources, whether human, material, or financial, is mainly due to a lack of anticipation, poor risk analysis, and excess optimism during ramp-up preparation. Generally speaking, proper planning of ramp-up projects involving project management practitioners as well as domain-specific experts is likely to lead to a

Table 2
Survey questionnaire.

Questions topic	Answer
Overview	
Company size	Small, SME, large
Business sector	List from national database
Product development	
Average product lifetime	< 1 year, 1–5 years, 5–10 years, > 10 years
Average New Product Development (NPD) frequency	> 1/year, 1/year, 0.5/year, 1/5 years, < 1/5 year
NPD outsourcing	Fully, partly, not outsourced
Production policy	MTS, MTO, ATO, CTO, ETO
Ramp-up projects and strategies	
Experienced ramp-up situations	Ramp-up of a new product, ramp-up of an existing product, ramp-down
Phase/step during which ramp-up planning arise	Design, prototyping, etc.
Departments involved in ramp-up planning	R&D, design, production, logistics, marketing, finance, HR, other
External partners involved	Customers, suppliers, sub-contractors, service providers
Ramp-up strategy overview	Rapid changes, incremental, other
Ramp-up strategy – existing product	Immediate shut down, gradual transfer, other
Criteria for defining the strategy	Speed, robustness, facility of change management, cost, other
Performance indicators to manage ramp-up	Speed, scrap rate, system robustness, other
Ramp-up duration	Weeks, months, year, more, other
Budget determination for ramp-up project	Yes/No
Experience and feedback	
Training sessions for the stakeholders involved	Yes/No
Involvement of temporary operators	Yes/No
Issues encountered during ramp-up	Time, quality, scrap, change, competencies, resources, capacity, cost, information, other
Solutions implemented	Open question
Supporting methods and tools	
Quality control during ramp-up	Yes/No
Cost control during ramp-up	Yes/No
Methods and tools used for ramp-up management	Quality control, cost control, risk management, simulation, data collection and analysis tools, agile methods, decision support and optimization, big data, other
Practicality of the methods and tools used	Likert scale
General ramp-up improvement options	Open question
Crisis impact	
Situations/issues experienced	Production shut-down, fall in demand, rise in demand, supply, storage, distribution, management
Emergency protocols defined and implemented to manage ramp-up and ramp-down	Yes/No

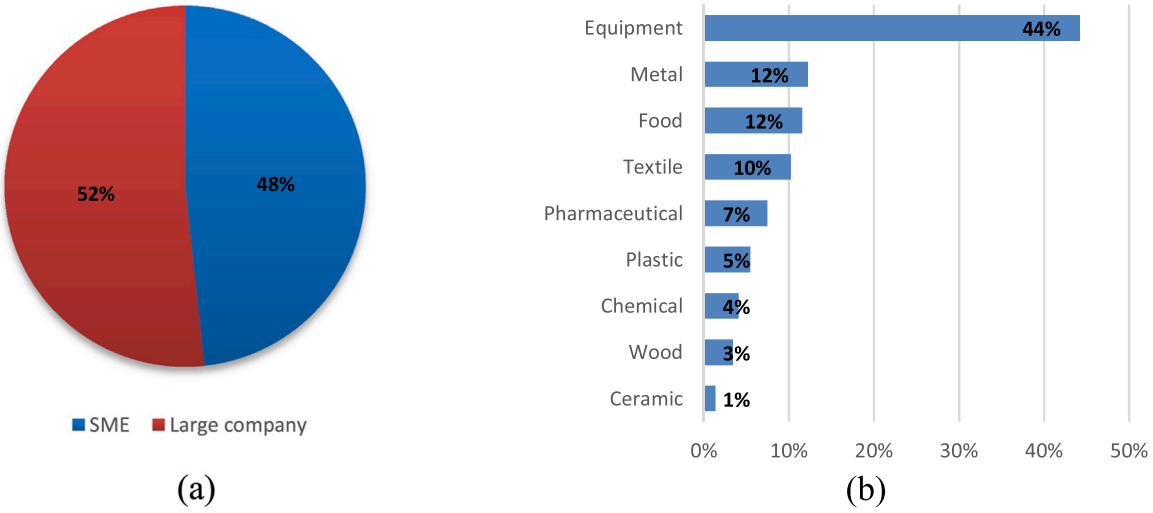

Fig. 2. Company size (a) and sector (b).

clearer definition of the scope and more realistic estimates of delay and cost. These efforts need to be backed up by risk management. Another explanation for these issues is the intrinsic uncertainty of ramp-up situations which cut across supply, demand, and internal processes and resources involved in the ramp-up.

While cost and delay issues are interrelated, they are also impacted by other issues such as quality, resources, and capacity management (total of 21 %). In addition, lack of resources and limited capacity are liable to increase delays and costs, especially if additional investment or outsourcing is required. These issues are heightened when the ramp-up projects and operations are not staffed with the right skills. Companies are relatively aware of these issues, since 12 % of the respondents mentioned skills as a challenge for ramp-up projects. Some of the respondents consider that ramp-up can be fostered by involving *skilled personnel* and intensive *training*. Surprisingly, change management was mentioned by only 9 respondents out of 147. This reflects a somewhat technical perspective of ramp-up projects that give less importance to their managerial dimension. In some situations where ramp-up involves innovative products or major changes to employees' *working*

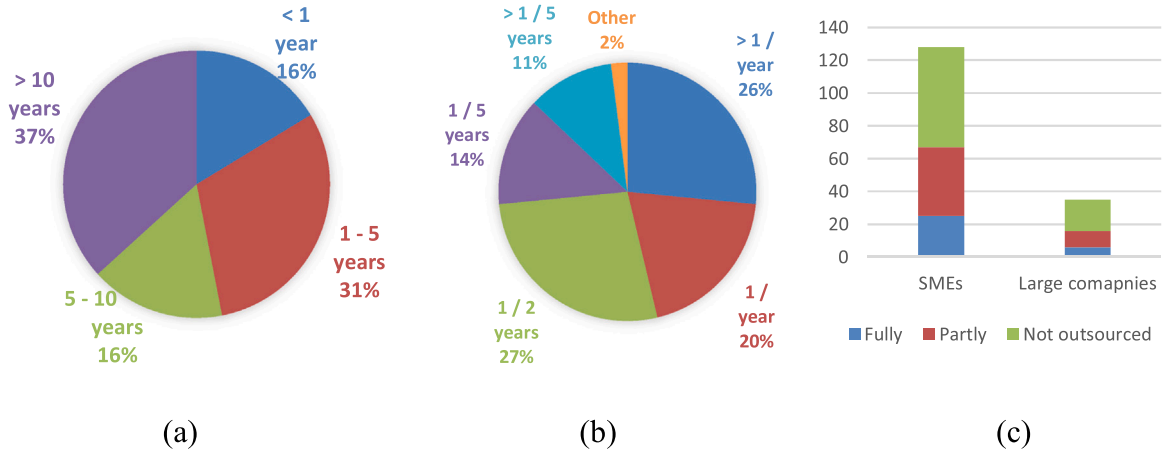

Fig. 3. Average product lifetime (a), NPD frequency (b), and ramp-up project outsourcing (c).

practices, change management was needed. Hence, a structured approach is very important in managing ramp-up projects that span technical and managerial aspects.

The survey also seems to show that some of the difficulties encountered during ramp-up are not only linked to the ramp-up itself but may also be related to other factors. This is particularly evident with issues of skillsets. These problems were encountered during ramp-up by about 20 % of the companies surveyed. Among these, however, more than half (55 %) declared that they had problems with skills during production before the ramp-up phase. The same is true for capacity issues. 19 % of companies faced this problem during the ramp-up, while 54 % of them had bottleneck problems before ramp-up. Hence, we can see that in some cases, the difficulties encountered during ramp-up may not be entirely related to the disturbances due to ramp-up, and may only be highlighted during the ramp-up phase.

The findings show that large companies face slightly more problems during ramp-up than smaller firms. Furthermore, quality issues affect more than half of the companies in the metal product and electrical or electronic equipment sectors. Delays are over-represented in the textile sector and, to a lesser extent, in the electrical and electronics sector.

Strategies and methods

The survey results indicate that many companies prepared the ramp-up upstream (Fig. 5a). Thus, almost 80 % of the companies surveyed (theoretically) take the question of ramp-up into consideration before the end of the design phase of a new product. This means that the issue of ramp-up comes quite early in the product design process, even if only 27 % of companies prepare ramp-up from the beginning of the design phase. Companies generally start planning the ramp-up project (e.g., define the schedule, budget, etc.) during the ramp-up preparation phase.

It also appears that few companies set up interdisciplinary teams to prepare ramp-up. Thus, many companies seem to entrust ramp-up preparations to a single department which often has little or no interaction with other departments. In 50 % of the companies

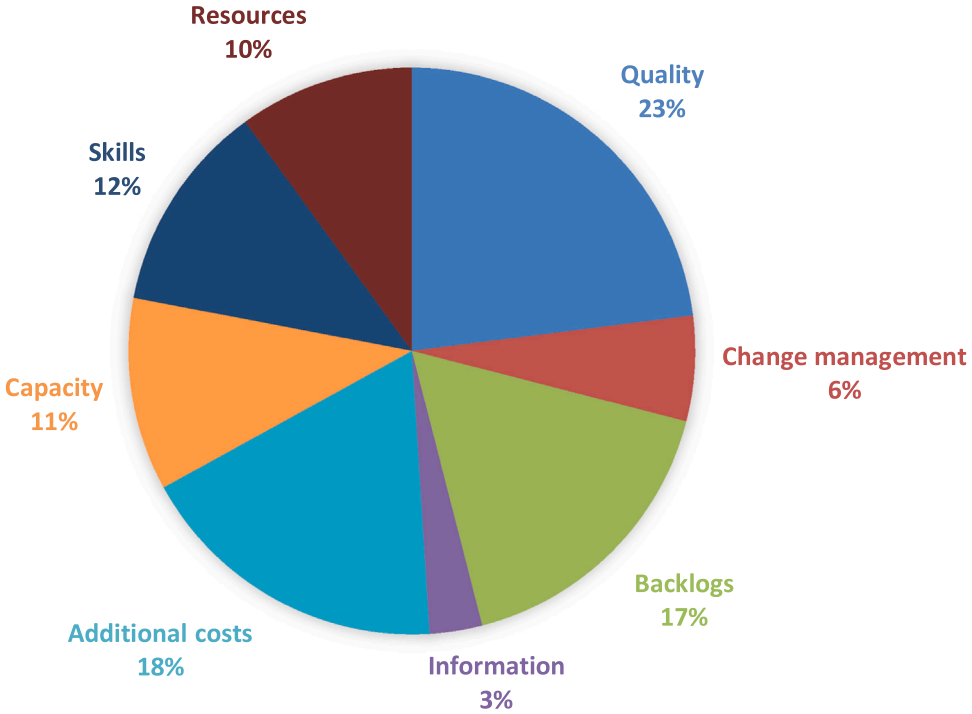

Fig. 4. Ramp-up issues identified.

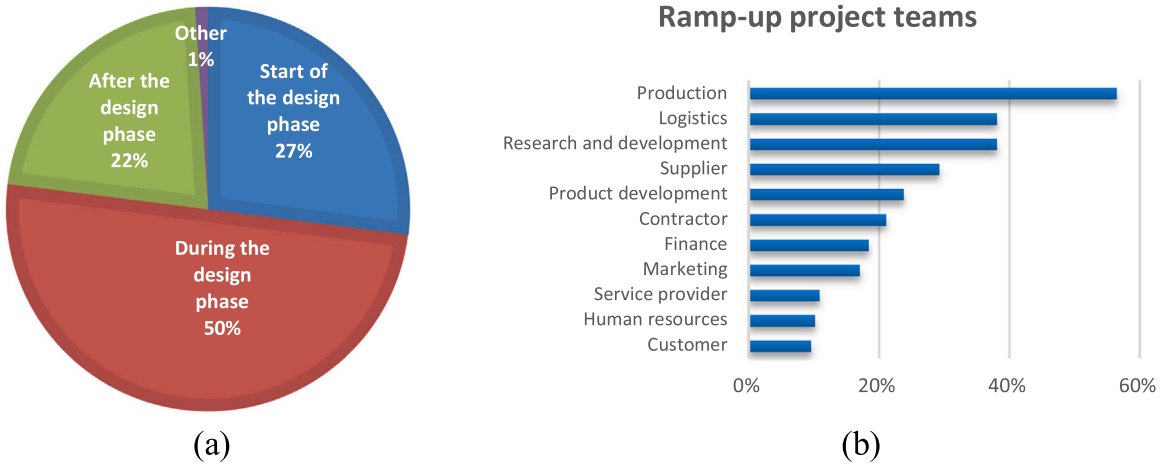

Fig. 5. Ramp-up planning (a) and team (b).

surveyed, only one department is involved in the entire ramp-up preparation. We may note that the choice of the department selected differs quite significantly in the companies surveyed with the production department most frequently involved (around 56 %), followed by the R&D and logistics departments (around 38 %), and then supplier and product development departments with a share of 29 % and 24 % respectively (Fig. 5b).

Anticipating ramp-up reduces risk to a certain extent. Indeed, the number of problems identified during ramp-up is lower for companies that start preparing for it at the beginning or during the product design phase (−5 %). On the contrary, the number of problems is higher for companies that only start preparing ramp-up once the product design phase has ended (+14 %). More specifically, there is a marked increase in delays (+12 %), mismanagement of operators' skills (+8 %), and quality defects (+7 %).

The survey identified three performance criteria for ramp-up projects, namely time, quality, and robustness (Fig. 6a). These criteria are usually defined based on initial ramp-up targets, which in turn are derived from company strategy. Time remains at the top of decision-makers concerns, since more than half of the respondents indicated that it is taken into consideration in managing ramp-up projects (54 %). The survey showed that there is a strong desire for many companies to design and implement a robust production system during ramp-up (34 %). Quality is recognized as a performance criterion for ramp-up projects in 30 % of the respondent companies.

The survey also looked at the strategies chosen by companies to conduct ramp-up (Fig. 6b). Most companies (74 %) appear to opt for the "step-by-step" strategy. This implies implementing gradual changes to reduce disturbances and facilitate change management. This strategy may be backed up by knowledge acquisition about the actual system allowing for adjustments. Firms' desire for a smoother transition process can also be seen in their decision to continue ongoing production with the precedent production system during the ramp-up phase, as well as by the high number of companies organizing training for their operators (71 %) during the ramp-up. Fewer companies opt for more abrupt changes: only a quarter of companies reported stopping their production completely during ramp-up.

The survey results do not enable us to judge whether one of the possible ramp-up strategies is particularly relevant. Indeed, neither the step-by-step strategy nor the shut-down strategy manage to limit the number of the issues encountered during ramp-up. Furthermore, the main issues (i.e., quality, additional costs, and delays) were found in similar proportion. However, it is clear from the results that production stoppage during ramp-up is a source of disruption, generating more problems and difficulties related to quality (+10 %), resources (+9 %), and change management (+7 %).

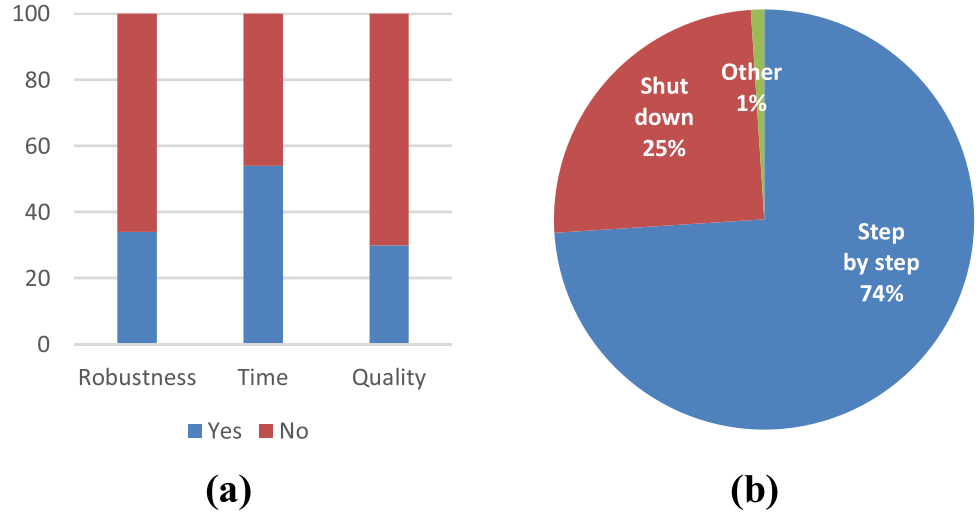

Fig. 6. Ramp-up project targets (a) and management strategies (b).

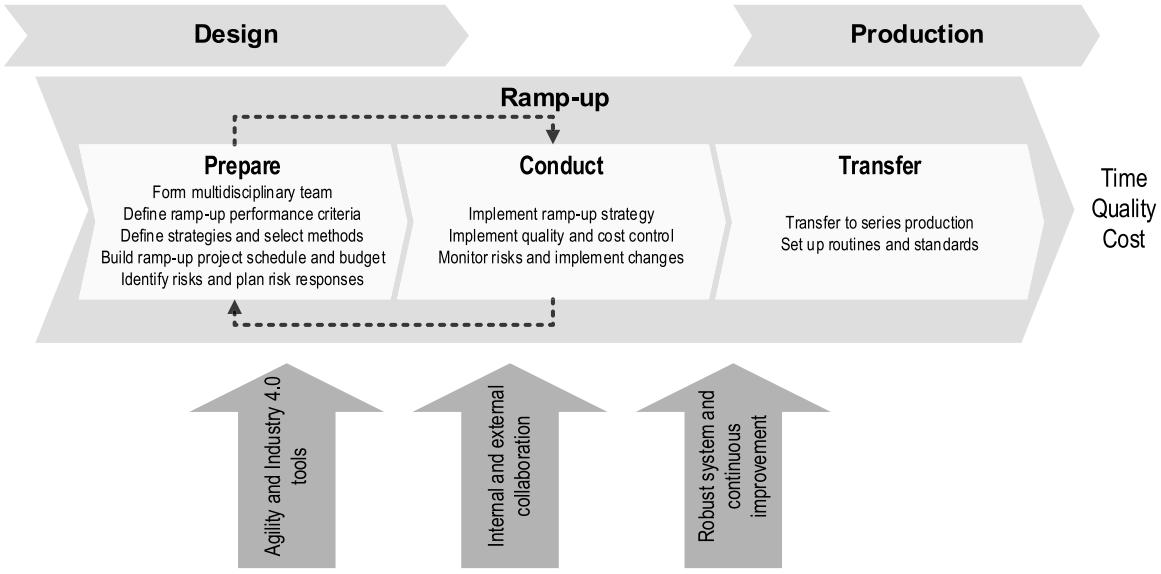

Fig. 7. Ramp-up projects management recommendations.

The aim to manage ramp-up projects is shown by the implementation of specific control systems, notably with the stepping up of quality controls during ramp-up (around 75 % of the companies surveyed) or monitoring cost systems (66 % of companies). The results showed that, without cost monitoring systems, cost overruns occur in about half the cases. When a monitoring system is put in place, cost overruns concern only 30 % of companies.

A summary of insights from the survey is presented in Fig. 7, which gives a structured map to plan and conduct ramp-up projects. Although the results mainly focus on planning and conducting ramp-up projects, it is important to clearly mention the transfer step, which also reflects the closure of the ramp-up project and transfer to series production. This phase is often implicitly mentioned when discussing ramp-up projects. Moreover, as shown in Fig. 7, ramp-up is consistently positioned with regard to design and production, with the idea of starting the ramp-up project early during the design process. Some of the most common targets for ramp-up projects are listed on the right-hand side of the figure. The bottom area of the figure highlights some key cross-cutting principles supporting ramp-up management, namely, agility principles, collaboration and integration, a robust system, and continuous improvement. These principles will be further discussed in the next section.

Ramp-up management principles

The survey provided some insights into recommendations for managing ramp-up projects. These recommendations help to structure the projects by focusing on the general scope of the ramp-up (the “what”). In addition, several working principles that apply generally to all the project phases can be derived from the previous analysis (the “how”), which are assumed to be among the drivers for successful ramp-up projects. These principles are interrelated and involve agility principles, collaboration and integration, system robustness, and continuous improvement. We discuss them in the next paragraphs. Decision trees were used to study the most influential factors on these drivers further, based on the survey results. These rely on tree-like models to make inferences about decisions and their consequences [13]. They are widely used in machine learning and other fields such as operations research. Decision trees were considered suitable for this study due to their intelligibility and their capacity to handle quantitative and qualitative variables. The nodes of decision trees represent the different variables, ordered according to their impact. The branches are labelled with the values separating the variables at the splitting points. The leaf nodes represent the outcome of a given path and are modelled by boxplots of the average rates. In the current study, the trees were generated using the *rpart* package (Recursive Partitioning and Regression Trees) available from the R software repository [57]. The ANOVA (Analysis of Variance) method was used to this end. The aim was to provide general insights into the most influential factors, so further comparative analysis of several methods and techniques was deemed unnecessary.

Agility principles

Agility is one of the keys to the successful outcome of ramp-up targets [9]. The survey showed that 30 % of respondents are aware of agile methods and use them in ramp-up, illustrating the importance of incorporating agility principles throughout ramp-up project lifecycles. With reference to the recommendations shown in Fig. 7, preparing and conducting ramp-up project activities should be conducted iteratively, enabling the plans to be adapted according to the knowledge gained after implementation. This process can be supported by proper knowledge management mechanisms at corporate level [60]. The length of iterations can be defined based on the company context, including changing customer requirements, supply constraints, etc. Continuously identifying and monitoring change requirements means the (re)design and production system can be adapted and the ramp-up strategy adjusted accordingly. It is also important to define the scope of the ramp-up project in terms of what should be done to reach targets, based on available data and estimates at a given point in time (e.g., product quality, process stability, demand forecast, etc.). A detailed plan can be defined for short-term actions, with only a draft plan for mid-term ones. The work should then be scheduled, and performance indicators defined to measure progress.

However, the use of agile methods depends on the company context (e.g., regulated sectors such as the pharmaceutical industry, or corporate culture with regard to agility versus plan-driven methods). The survey revealed the role of NPD frequency in using agility methods. In Fig. 8, we can see that, generally speaking, the more frequently NPD projects are launched, the more agility methods are used (nodes 13–15). The company’s experience across ramp-up projects can foster the use of agile methods. This is in line

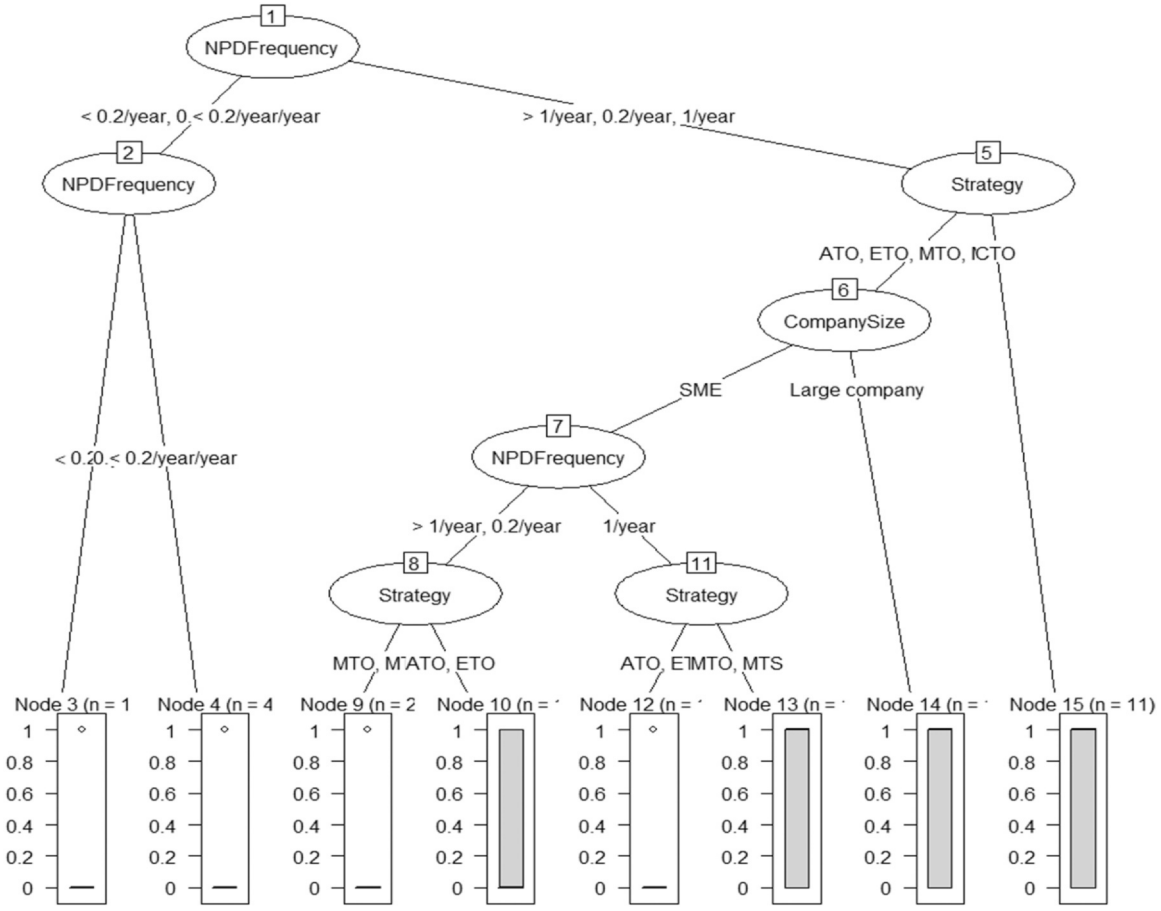

Fig. 8. Factors influencing the use of agility methods.

with the idea of knowledge spillover across ramp-ups [39], which also means that agility improvement goes hand in hand with knowledge creation and transfer.

Collaboration and integration

One of the key points in ramp-up projects is collaboration between all the stakeholders that directly or indirectly contribute to or are affected by ramp-up. This includes several internal departments, such as sales, logistics, production, product development, management, human resources, and finance, but also some external players involved in the ramp-up project (e.g., customers, suppliers, service providers). As shown in the literature, collaboration is important to meet ramp-up objectives and to reduce time-to-market [5,55]. One prerequisite of internal collaboration within a company is early ramp-up planning. Fig. 9 shows that ramp-up duration is generally higher when planning starts after the design phase (AtD) (nodes 8 and 9). The average duration falls when ramp-up planning begins during the design stage (DtD) (node 6) or at the beginning of the design stage (BoD) (nodes 4 and 5). Surprisingly, involvement of the logistics department may have a negative impact on the ramp-up duration. Conversely, marketing department involvement can lead to shorter ramp-up. This could be explained on the one hand by increased project complexity when the logistics department is involved (e.g., large projects with a significant impact on logistics), while on the other hand, marketing may boost added value by improving forecast accuracy and fine tuning ramp-up strategies, thus limiting delays and workarounds during ramp-up.

It is especially important to improve information communication and coordination between departments in a context of uncertainty and disruption [25,26,5]. Forming a specific interdisciplinary team devoted to the ramp-up and including all the departments affected by it is likely to considerably facilitate internal collaboration. It is important to do this as soon as possible, notably to define ambitious but accessible targets and to determine all the resources, whether material, human, or financial, needed for the ramp-up. This collaborative work involves regular meetings, specific communication channels, and the development of collaborative tools. In addition, building an efficient information system is likely to improve collaboration by establishing more fluid communication and facilitating data sharing among all the stakeholders. Collaboration may also help to solve the difficulties encountered during the ramp-up. For instance, problem-solving workshops to deal with the challenges encountered during ramp-up are widely found in companies, and their usefulness is strengthened by involving people with various skills and from different horizons.

Relations with the supply chain is another crucial issue. Companies' supply chains tend to be highly complex, involving distant or foreign partners. They are therefore often relatively fragile and subject to hazards that hamper the companies' activities. When timeframes are uncertain, dealing with supply chain-related issues is even more important (e.g., secure flows, backup plans) in the organization of mass production. Thus, it is useful for companies to diversify their suppliers so as to avoid being too dependent on one partner and having the potential to negotiate lower prices. Working with local supply chain players can reduce shortage risks and transport issues. Indeed, such choices tend to reduce transport times and avoid issues with border crossings and customs. They can also help to streamline the entire company supply chain. Another possible means of improvement could be to reduce the number of intermediaries in the supply chain. Risks are automatically lower, but it could have negative fallout, especially in terms of cost, quality, or

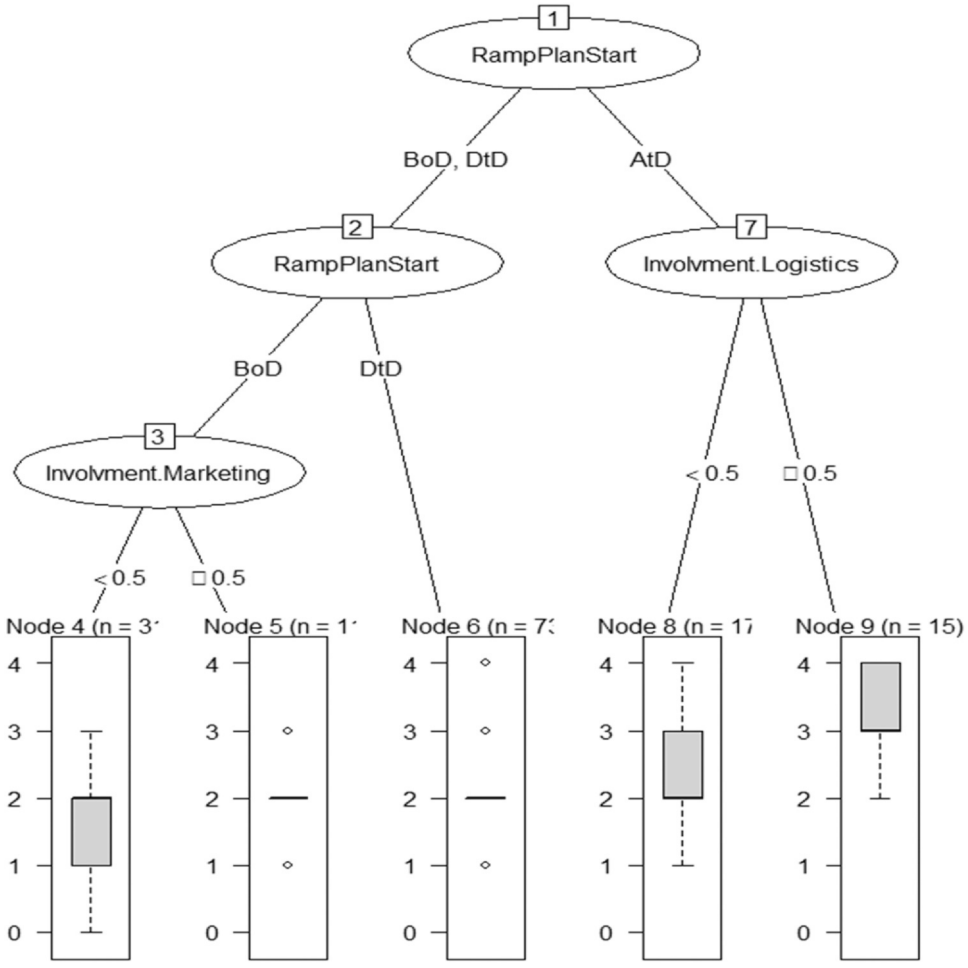

Fig. 9. Collaboration related factors influencing ramp-up time.

deep-seated changes that are not necessarily easy to implement in troubled or uncertain contexts. More generally, fostering collaboration and building trusting relations with supply chain actors needs to be stepped up. Transparency and clear communication are assets for companies, especially if ramp-up issues are recurrent. This all requires upstream anticipation work and the specific investment of some employees, in line with recent research on the role of communication and information-sharing within ramp-up situations. Gesell et al. [26] empirically determined that proper communication between buyers and suppliers has a positive effect on ramp-up performance. More generally, the idea of information-sharing and information quality has been presented as a key issue in dynamic environments such as ramp-up [25,26].

System robustness and continuous improvement

Another area of work concerns system robustness. A combination of flexibility and standardisation with the supply network is paramount for successful ramp-up projects. This involves both processes and workforce. Writing reference documents and defining best practices improves the quality of the production process and prevents companies from becoming over-dependent on experienced or specialized operators. It also accelerates the learning process and contributes to knowledge accumulation, which is always essential during ramp-up. Developing operators' versatility may be positive for companies, not only during ramp-up but also in other product lifecycle phases. This can help to address the issue of skills raised by 20 % of respondents in the survey.

It is also possible to introduce ways to make the production lines more flexible, notably through more versatile machines and the development of reconfigurable automation. Such practices are likely to lead to more flexible capacity and help address issues related to capacity at large. In fact, 19 % of the respondents deal with limited capacity problems during ramp-up, although around half of them experience the same problems in serial production. This raises another issue related to corporate strategies in the long run, namely, investment in terms of supporting both scalable and convertible resources to deploy during production ramp-up.

In addition to a suitable infrastructure, the survey revealed some methods and approaches that promote the timely execution and budget compliance of ramp-up projects. Interestingly, risk management is at the top of these approaches, as highlighted in Fig. 10. When implementing this approach, timely execution and budget compliance can generally be met (node 9). Other approaches include data analysis and quality control, as well as introducing training. Delays and cost overruns mainly occur through lack of training (node 4) and quality control. Although these approaches also relate to ramp-up project performance, they play a key role in system robustness as they help the personnel to be ready for and to deal promptly with disturbances.

Discussion and research perspectives

The recommendations made in this paper provide guidance for project managers and decision-makers involved in ramp-up management, making it more agile and more efficient. The recommendations are

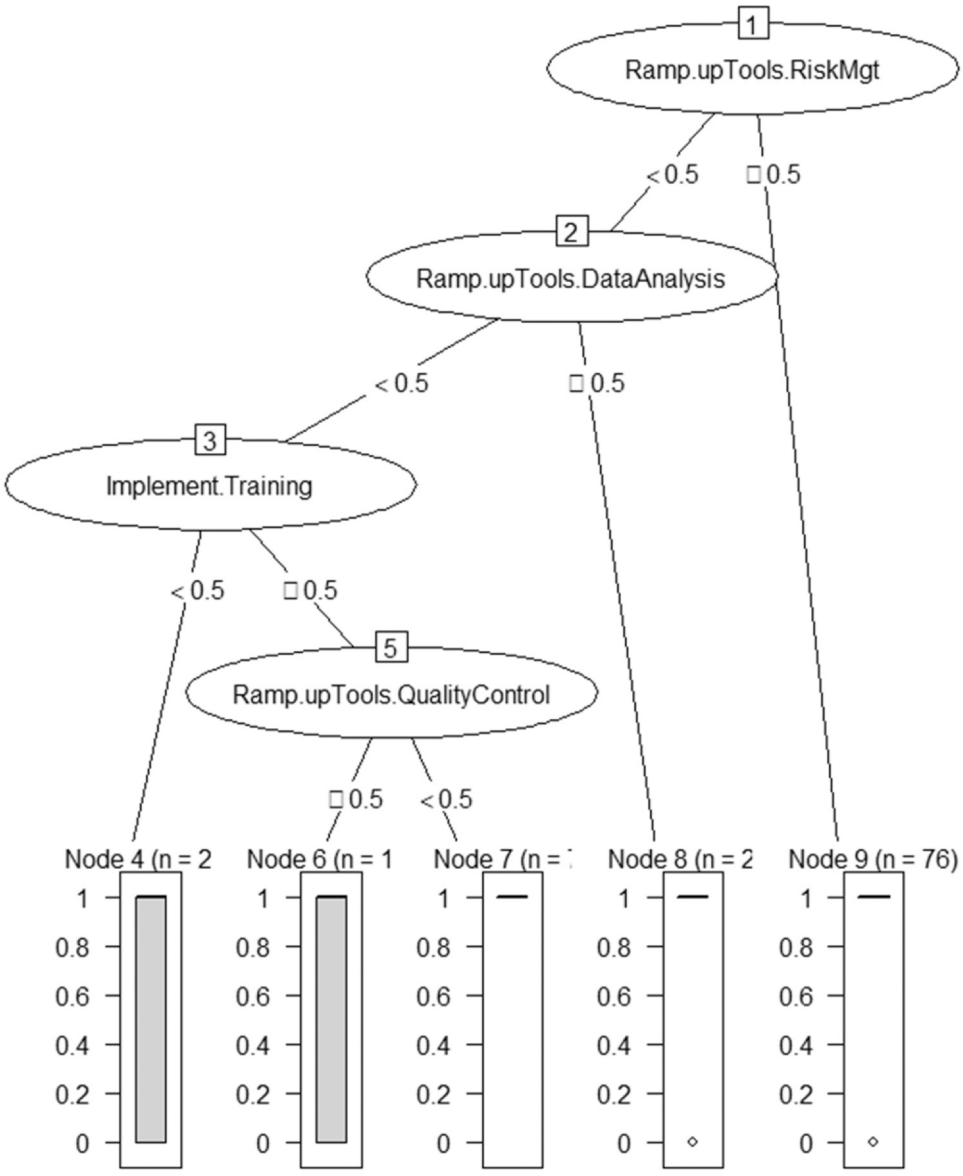

Fig. 10. Factors influencing timely execution and budget compliance of ramp-up.

consistent with a project management perspective that is well suited to ramp-up. In this sense, and similar to Brandl et al. [11], the current paper contributes to reinforcing the operationalisation of agility and agile project management in manufacturing, with a specific focus on ramp-up.

Our research complements the existing literature in that it offers a holistic approach to managing ramp-up projects. As such, it provides a framework for articulating existing contributions, and adds further insights to improve ramp-up efficiency. In fact, the current findings are rooted in the conceptualisation of ramp-up and ramp-up management set out by Berg and Säfsten [8], Christensen [17], and Schmitt et al. [50], among others, which helped us to define the general scope of ramp-up projects. Research on decision support is of particular interest in the planning phase (Prepare) of ramp-up projects [30,53,20] and the execution phase (Conduct) [23,19]. Furthermore, work addressing learning and knowledge management in ramp-up projects is useful for the transfer to production phase (Transfer) and for the entire lifecycle of a ramp-up project, and even across ramp-up projects [39].

The results presented in this paper come within a research continuum that can benefit from several perspectives, some of which are (partially) revealed by the current paper, (i.e., product development and interactions between production teams and processes, quality management during ramp-up, methods and tools supporting ramp-up projects, the decision-making process). Some of these are identified by the literature in the field, such as service ramp-up management and Industry 4.0 potential.

The survey revealed the problem of ramp-up planning during product development. In fact, despite respondents' awareness of ramp-up requirements from the early development stages, project planning does not formally occur before the start of the ramp-up phase. Further research is required to bridge the gap between product development teams and production teams towards more integrated planning of ramp-up projects [2]. It also involves change management and increased awareness of agility and resilience requirements. Furthermore, as the field studies show, quality is one of the main issues companies struggle with during ramp-up. Further investigation of the origins of such issues is thus required with, ultimately, the development of appropriate tools specifically tailored to the ramp-up phase. One important question that needs to be addressed on this point relates to the balance between quality assurance and standardisation on the one hand, and agility and flexibility on the other. In fact, the ramp-up phase is characterized by frequent changes and requires more agility, which may be seen as a

burden to quality assurance and process stabilization. The challenge is how to keep up with the pace of "stable change".

One more perspective involves the identification of specific methods and tools in given sectors that are likely to support each of the ramp-up project phases, especially the "Transfer" phase. This perspective can benefit from recent work on commissioning in the ramp-up context [12,46]. Another perspective is that of clarification of the decision-making process in a flexible and quite detailed way, taking the risks at each stage of the ramp-up project into consideration. A preliminary study was recently conducted by Mamaghani and Medini [42] which could support this process. However, in all cases, further empirical testing is needed to gain more insights into ways to improve the recommendations made in this paper. Case studies would be useful to explore such perspectives.

Looking into the scientific literature, two general perspectives can be identified. The first one involves extending the research to service ramp-up. In fact, most of the literature and the companies surveyed deal specifically with the product domain, while service ramp-up has received little attention to date [31]. The second perspective involves investigating the Industry 4.0 potential to improve ramp-up projects. The idea is to identify ways to benefit from Industry 4.0 technologies and design principles [32] to improve the performance of ramp-up projects. This is in line with the work of Schmitt et al. [50] and Letmathe and Rößler [40] who discussed the potential of Industry 4.0 to improve agility and ramp-up.

Conclusion

In a context of increasing turbulence and volatile markets, ramp-up projects have more than ever become a driver for change. Proper guidance is thus needed to overcome the challenging management of ramp-up. The current paper contributes to this objective by providing an updated overview of ramp-up concepts, challenges, and strategies, providing a structured set of recommendations for managing ramp-up projects. Further empirical and theoretical research is still needed with regard to (agile) ramp-up management in order to seize the opportunities and address the risks raised by fast growing technologies such as artificial intelligence, and emerging business trends such as manufacturing as a service.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work is partly supported by the German-French Academy for the Industry of the Future through RAMP-UP II project.

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