Dynamism in complex engineering: explaining uncertainty growth through uncertainty masking

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Abstract

The development of uncertainty over the progression of a project (i.e. dynamism) is a central issue in engineering management; however, it has been little explored. This paper answers the question of how uncertainty develops over the course of complex engineering. We present a case of a renewable energy power plant where we performed content analysis on over 54,000 e-mails. The findings reveal a new mechanism affecting uncertainty development. We call this mechanism '*uncertainty masking*' and define it as: the process through which a '*root uncertainty*' is misidentified by the project team, resulting in the creation and management of a '*symptomatic uncertainty*'. Root and symptomatic uncertainty types compound over time and hamper uncertainty resolution, leading to growth in level of uncertainty during later project stages. We describe the impact of uncertainty masking on the u-shape level of uncertainty in the case project. This research contributes to the engineering-management literature by explaining observations of uncertainty growth, which existing theory is unable to explain. We thus significantly advance uncertainty theory in engineering management.

Managerial relevance statement

This research identifies a core challenge for engineering managers, particularly in complex engineering. Managers need to be able to correctly identify the uncertainty types their engineering project face. Specifically in complex engineering, this may be a significant challenge as shown by this research. For example, technical uncertainty may be misidentified by the project team because it creates challenges for supplier management or internal organisation. However, identifying uncertainty types correctly reduces the potential adverse effects of uncertainty in the later project stages, where the project team can deliver and integrating engineering outputs instead of re-designing and re-developing technical parts.

Keywords: uncertainty, complexity, content analysis

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I. Introduction

Uncertainty describes a lack of understanding or knowledge in the form of deficiencies in any stage or activity of the process that can be characterised as not definite, not known, or not reliable [1]. It is an important driver of activity in innovation [2], [3] and engineering management [4]–[6]. Prior work, particularly in radical innovation, has highlighted the potential adverse effect of uncertainty on project activities and performance [2], [7], [8]. Here, uncertainty multiplicity has been described, where the level of uncertainty is affected by multiple uncertainty types [2], [9]. For example, highly innovative products create high levels of technical and market uncertainty [4], [5], [10] while other relevant uncertainty types include resource uncertainty (fluctuations in availability of, e.g. finances and employees) and organisational uncertainty (internal restructuring, strategic changes etc).

Despite the importance of uncertainty in engineering management and innovation, there are two important gaps in current understanding. First, in terms of setting, little is known about uncertainty in the context of complex engineering, such as large-scale infrastructure, rail networks, or wind farms. The importance of uncertainty in complex engineering can be inferred from observations such as the difficulty in achieving complete understanding [11] and predicting the effects of decisions [12], as well as the limited scope of control of individual engineering managers [13]. Here, high complexity decreases the project team's ability to understand the problem [11], [12] resulting in reduced performance [14], [15]. As a result, the management of complex engineering is challenged by the failure to effectively describe and resolve uncertainty [14] as evidenced by frequent cost overruns, delays [14], [15], and decreased solution quality [12].

Second, current uncertainty theory offers extensive conceptualisation and empirical description of the overall *level of uncertainty* in terms of *uncertainty multiplicity* (the simultaneous existence of multiple uncertainty types) [2], [3], [5], [8]. Together these offer a robust means of describing static uncertainty at a specific moment in time. However, theory is less well developed with respect development of uncertainty over time. Specifically, current research either neglects development all together [4], [5] or assumes uncertainty reduction via uncertainty resolution [2], [11], [16], [17]. While the idea of uncertainty reduction is somewhat established, the nuances of its effect and the more general development of uncertainty over the progression of a project have not been studied in detail. This leaves major unresolved questions regarding the mechanisms through which uncertainty develops over the course of an engineering project, and importantly, limits explanations of dynamics in this development.

This research aims to investigate the development of uncertainty over the progression of a complex engineering project, by answering the following research question: *How does uncertainty develop dynamically over the course of a complex engineering project*? This research builds on a conceptual framework of uncertainty proposed by O'Connor and Rice [2] in radical innovation. We build theory by presenting empirical insights from a case of a renewable energy power plant where we analyse e-mail communication over the whole project duration via content analysis. This research contributes to the engineering management literature by refuting the assumption of uncertainty resolution as the only process affecting the development of uncertainty. Specifically, we identify a fundamentally new mechanism acting in opposition to uncertainty resolution by creating uncertainty growth. We call this new mechanism '*uncertainty masking'*.

II. Theoretical background

Complex engineering describes the intersection of product complexity and organisational complexity [18]. Complex products are characterised by numerous design parameters and long development times [11], while complex organisations integrate contributions from a large number of people [19], with numerous disciplinary backgrounds [13]. This is distinct from innovativeness, which describes the level of newness of a product with regard to the customer, provider firm, and industry [20]. Lee [21] differentiates functional products (with long product life cycles and stable demand) from innovative products (with short life cycles based on fashion content and unpredictable demand). Complex engineering can relate to both product types; however, many complex products such as wind turbines, power plants or surface ships can be characterised as functional [21].

Complex engineering is closely linked to uncertainty because of the degraded ability to build a cohesive understanding of the engineering task itself and its completion [15]. For example, Yu et al. [11] describe how designers fail to accurately represent complex product requirements and thus struggle to find accurate and relevant solutions. This understanding determines project team's uncertainty [22], [23], creating a critical link between complexity and uncertainty [18]. Thus, while existing research has provided important explanatory insights of uncertainty in radical innovation [2], [3], [5], [24] these cannot be assumed to apply in complex engineering, making this a critical gap in the literature.

A. Uncertainty in complex engineering

Early characterisations of uncertainty in engineering management focused on uncertainty as a consolidated phenomenon, describing the static level of uncertainty in terms of the overall degree of the lack of understanding [3], [5], [6], [25]. High levels of uncertainty distinguish highly-unpredictable situations due to, for example, highly volatile environment, highly ambiguous tasks, or unclear organisational processes. Low levels of uncertainty, in contrast, define relatively predictable situations where, for example, engineering tasks are relatively clear, design details are specified and organisational structures and processes are defined.

These early models typically assume linear reduction of uncertainty over project progression via uncertainty resolution until the uncertainty is fully resolved upon project delivery [3], [5], [6], [25], [26]. For example, Yu et al. [11] and Wynn et al. [17] suggest that technical uncertainty should reduce over the course of the project as the teams' knowledge regarding design parameters and their coupling increases. These models lack more nuanced insights into the dynamic development of uncertainty over time based on, for example, effectiveness of response mechanisms. For example, Leenders et al. [27] explicitly highlight the need to develop theory sensitive to team composition and dynamics. Similarly, Holland [28] has described the dynamism of individual's perceptions under complexity, from which more varied uncertainty dynamics can be inferred.

Later models have elaborated uncertainty theory by describing uncertainty multiplicity, replacing the previous conceptualisation of uncertainty as a consolidated phenomenon [2], [4], [29], [30]. This resulted in the elaborated characterisations of multiple uncertainty types, each of which contribute to the level of uncertainty. Table

1 lists some of the major conceptualisations of uncertainty types in engineering management. These efforts have resulted in a more nuanced characterisation of static uncertainty, understanding sources and manifestations within engineering projects. However, these models are still based on static descriptions of level of uncertainty and maintain the general assumption of uncertainty reduction as the primary driver of development [11], [17]. Explanatory insights into the development of uncertainty over the progression of complex engineering project are still missing. While many authors acknowledge the importance of development of uncertainty during the engineering process [2], [24], [31]–[33], descriptions of dynamics in this context are missing. The general assumption of reduction via uncertainty resolution is still prevalent, despite suggestions from the design and human perception literature that uncertainty might be much more dynamic than previously assumed [23]. These are important gaps this paper aims to address.

<Please insert Table 1 about here>

B. Conceptual framework

To develop a conceptual framework needed for empirical investigation of our research question, we focus on the latest insights from theory in the field. Specifically, O'Connor and Rice [2] offered a first consolidated framework of *level of uncertainty* with *uncertainty multiplicity* derived from four uncertainty types in radical innovation: *technical*, *market*, *organisational,* and *resource* uncertainty. We use this framework as the basis for our static conceptualisation in complex engineering. In terms of development of uncertainty, current theory offers only one major explanatory mechanism for changes in level of uncertainty i.e. reduction via *uncertainty resolution*

[2], [11], [16], [17]. We thus use this as the starting point for our investigation of development of uncertainty.

Technical uncertainty describes the degree of understanding regarding the scientific knowledge underpinning a new product and the ability to convert this knowledge into a reliable, cost-efficient technology platform that is manufacturable [6]. Technical uncertainty can arise from the use and integration of new technologies [8] with the potential of unknown interdependencies being of particular concern in complex engineering [11].

Market uncertainty refers to difficulties in understanding customer needs and translating these into product characteristics [34], [2]. It arises because of difficulties in predicting market opportunities for radically new products [10]. Milliken [35] describes environmental uncertainty more generally highlighting that in managerial decision making, the wider external context affects decision outcomes. In innovation, however, market uncertainty has received wider recognition.

Organisational uncertainty arises from inside the focal organisation [2]. It stems from the need for internal communication and information processing [36], [37]. It captures the strategic fit of the project within the wider organisation, which affects the availability of internal resources [38]. This can manifest in organisational resistance, competency gaps, lack of continuity and persistence, inconsistency in expectations and metrics, and changes in strategic commitment [2] leading to unstable funding availability over time [38]. For example, O'Connor and Rice [2] showed how organisational dynamism affects project outcomes in radical innovation.

Resource uncertainty stems from the availability of external resources, which can exhibit unexpected fluctuations and bottlenecks in the amount and timing of supply [2]. For example, product parts that require detailed technological capabilities may need to be resourced from external suppliers [2]. In complex engineering, external partners such as suppliers and consultants often provide the detailed technological knowledge needed [19].

III. Method

To investigate the RQ, we apply an exploratory research approach by investigating a single case. This is a suitable method for three main reasons. First, studying the behaviour of complex systems such as complex engineering has been highlighted to require investigation via case studies [39], [40] because system behaviour can vary between systems and sub-systems. Case study methodology has also formed the foundation of much of the uncertainty literature due to the importance of context on level and nature [2], [30]. Second, a case study offers rich data that enable an in-depth analysis of the studied phenomenon [41]. The lack of prior explanatory theory requires us to study one case in-depth to identify the fundamental mechanisms [42]. Third, case-study research is applicable when there is a lack of extant theory explaining the investigated phenomenon [43]. As highlighted in Section II, current theory on complex engineering is still emerging, and specific theory on the level and nature of uncertainty is sparse. In particular, our analysis provides a basis for comparing our work with other case-based studies of complex engineering [18], [44]–[46].

A. Case selection

The case was chosen based on three theoretical relevance criteria [41]: complexity of the engineering task, product innovativeness, and evidence of uncertainty [2], [21];

and the practical criteria of completeness in terms of project activities and data access. Data access was gained via the case company who were the primary responsible for the engineering work.

The case study focused on a renewable energy power plant designed to lower emissions and increase net efficiencies in operational costs and use of biomass. This case offered an example of complex engineering [47] with numerous innovative elements. Innovation was needed in numerous technical systems that had to be specially developed, customised or sourced based on the biomass type, customer needs, and new technological advances. This was based on the large number of design parameters, with the product being a complete renewable energy power plant (based on continuous innovation from existing plants) and the large number of people involved [19]. The internal team at the case company consisted of more than 90 individuals, who interacted with over 160 additional project participants distributed across more than 50 partner organisations. These were geographically dispersed, with the case company split between Scandinavia and the UK, and major partners in the UK, Italy, Germany, Poland, and Denmark. The case company coordinated all activities with construction partners, manufacturers, and components providers.

The case project was organised into 13 product sub-systems and was completed from April 2009 to June 2014. The case project covered four stages: conceptual design, detailed design, system integration, and construction. These stages differed in terms of the level of project activities, involved stakeholders, and the engagement between the project partners as summarised in Table 2. In the conceptual design stage, the case company focused on adapting plant features from prior projects to fit the new circumstances and requirements of the current project. This stage included activities such as identifying and contacting possible suppliers, setting up internal operations, and coordinating with the client and different sub-system teams regarding the product specification. In the detailed design stage, the case company split the project team with respect to a number of specific product assemblies. Here, each sub-team comprised specialised members of the case-company, partners, and suppliers, working with relative autonomy following clear specifications. In the system integration stage, product-assembly activities were unified and potential interdependencies and problems were identified and resolved. In the construction stage, the plant was built and commissioned on the final site. Despite the definition of a formalised stage gate process the gates were not rigorously enforced as cut-off points across the whole project. Instead there were overlaps with some product assemblies entering a stage earlier than others. This was due to the interconnected nature of the product, where some elements were required to progress before others could complete a prior stage. Thus, the stage gate was used as a reference for project progress only. The presented case provided unique data access offering in-depth insights.

<Please insert Table 2 about here>

B. Data collection

The empirical data were collected from multiple sources of evidence [41], used to characterise and triangulate the level and type of uncertainty throughout the project. The theoretical focus on uncertainty lead to a natural empirical focus on observing its occurrence instantiated in the communication between team members, following similar analyses found in the engineering management literature [12], [13]. Thus, data collection included the entire set of project-related e-mail communication. E-mail communication is ideal for this research for two reasons: i) it represents the uncertainty perception of an individual, allowing for the evaluation across team members; ii) it represents temporally distinct relational events, allowing for the evaluation of dynamic development over time [27]. Further, e-mail has been described as key to work coordination [48], information sharing [49], and relationship-building [19]. E-mails enable both team- and taskwork, particularly in large, distributed organisations as in this case [48]. Thus, e-mails form a de facto archival record of uncertainty in engineering work.

The collected data included the data (email corpus) and metadata (date, email folder, sender and recipient) for the entire set of project-related e-mail communication. In total, more than 54,000 individual e-mails were collected. The case company systematically archived their e-mail communication in compliance with regulatory requirements, and in case of litigation or internal investigations. All e-mails were pre-sorted by employees into pre-defined folders, such as individual suppliers, client, internal communication, consultants, and shipping to the final product site. The folders mirrored the internal division of project activities, which was also applied to log hours and other internal processes. This ensured that the structure and meaning of the folders was well known by the employees.

Qualitative information on the case company and project was gathered to familiarise the researchers with the context, triangulate findings, and provide further depth [41]. Pre-existing process documentation, such as meeting notes and direct observations, provided understanding of working practices in the organisation and its partners. In addition, eleven unstructured and exploratory interviews were conducted with a range of management staff associated with the project, including the Vice President of Operations and Engineering, and the Technical project manager. These provided insights on the organisational structure, process architecture, time planning, and process stages.

C. Data analysis

The unit of analysis is the complex engineering project. All data were analysed to obtain an overview of the case project and the related activities. The e-mail data were iteratively examined [47] using both quantitative content analysis and qualitative approaches [47]. Data analysis was applied in four steps [50]–[52] as summarised in Table 3.

<Please insert Table 3 about here>

First, our structured set of text containing email communication, i.e. the e-mail corpus, was sorted into a timeline with regard to the project stages and divided into ten corpus segments (a standardised number of e-mails useful for comparison over time [53]). Corpus segments are needed when the number of e-mails varies significantly between project stages to enable validity of the presented results in terms of comparing corpus segments [50], [52]. The criteria used to determine the number of corpus segments was: i) largest segment size to maximise robustness; ii) the minimum size of one corpus segment results from the project stage with least e-mails [53].

Second, e-mail content was qualitatively coded to determine the predominant focus of communication. This was done inductively using the company-sorted folders and meta-data tags to allocate each e-mail to a communication focus in relation to the uncertainty types defined in our conceptual framework (see Table 2). To ensure internal validity [47] and the suitability of the folder structure, we performed in-depth analysis of a randomly selected sample of e-mails [50], [52]. This process showed reliability of higher than 98%. The second step resulted in three folders: Resource, Organisational, and Relational.

Third, the e-mail corpus was quantitatively analysed using content analysis because it provides an indirect and nonintrusive approach [40] that enables the quantification of qualitative communication [52]. To study 'real life' data (such as emails), content analysis provides a greater level of ecological validity in comparison to more intrusive research methods (e.g. interviews) [54]. This approach aligns with similar studies in the engineering management domain, especially when studying team work [19], [54], [55]. Specifically, we used a dictionary for content analysis where we used word frequency is an indicator of cognitive centrality or importance for the speaker or writer [40]. This has been previously demonstrated on uncertainty [23]. The dictionary was based on the literature in uncertainty assessment and elicitation [56], uncertainty assessment in scientific practice [57], and engineering management [1], [35]. Further, synonyms were included using major dictionaries such as the Oxford English dictionary, Roget, and Merriam Webster. Because some of the e-mail communication was in a Scandinavian language, the initial list of terms was translated and verified with a native speaker. The dictionary was further verified empirically on the data set through inductive, in-depth empirical analysis of specific term use in context [50]–[52]. Theoretical and empirical validation was iterated until a final dictionary emerged [52]. For this step, we utilised Python applying the text processing library NLTK and the Pandas library for data analysis. Table 4 depicts the final dictionary used for data analysis. For the purpose of the analysis we used truncated terms (marked with an asterisk) to include all possible linguistic variations of the term.

<Please insert Table 4 about here>

The quantitative analysis included a sequence of calculations to measure the relative changes over time in uncertainty [52], [58]. In a first step, the frequency of each dictionary term was counted within each corpus segment. Then, this frequency was normalised longitudinally for each dictionary term to ensure equal evaluation of each uncertainty term from our dictionary, irrespective of the intensity of their use. The normalisation resulted in a measure between 1 (max) and 0 (min) representing changes in the use intensity of that term over time. These normalised values were summed for each of the dictionary terms and corpus segments to provide a measure for the relative intensity of all uncertainty terms in each corpus segment. Finally, these values were normalised longitudinally regarding the total measures per corpus segment. This resulted in a measure where 1 means the maximum intensity in the use of uncertainty terms among all corpus segments and 0 means the lowest intensity in the use of uncertainty terms among all segments. This normalised measure is used to present the quantitative findings throughout this paper. These quantitative results were triangulated with the interviews to contextualise them with respect to the project's organisational structure, process architecture, and progression.

Fourth, we analysed the e-mails qualitatively to characterise the uncertainty types. Specifically, we analysed a sub-set of the e-mails, which had a high count of terms from the uncertainty dictionary. We ensured internal validity [47] by including a representative sample of e-mails from each stage of the development process (Output Step 1) and from the different folders of communication (output Step 2). Here, the qualitative interviews and secondary data enabled us to triangulate our insights to ensure construct validity [47]. Further, we followed the e-mail trail in our qualitative analysis to identify how uncertainty originated, propagated, and changed within the team over the course of the project. This confirmed the suitability of the folder structure for communication focus (from Step 2).

IV. Findings

The analysis revealed a u-shaped level of uncertainty, being highest during early and later stages and lowest in the detailed design stage. Furthermore, we observed uncertainty multiplicity, where each project stage contained a mix of uncertainty types with no single uncertainty type being dominant throughout. Further, the mix of uncertainty types varied from stage to stage. We found three main uncertainty types (Output of data analysis Step 2): two from our conceptual framework: resource uncertainty and organisational uncertainty, and an additional uncertainty type. This additional type was coded as *relational uncertainty* due to the focus on the relationships with external stakeholders, including suppliers of product parts and components, other long-term service providers, and the client. Relational uncertainty was perceived in all stages of the case project, however, its level and specific causes changed over time. In the conceptual design stage, relational uncertainty arose from activating the project team and relevant external stakeholders and the need for clarification of technical specification with suppliers. In the detailed design stage, it arose from the development of components and assemblies by suppliers, and the need to ensure information exchange and continued collaboration. In the later project stages (system integration and construction), it arose from discussions with suppliers and partners regarding delivery delays, damage to components, invoices and payments, and compliance with regulatory and technical requirements. Figure 1 depicts this development of uncertainty across the four project stages with the normalised scale between 0 (min) and 1 (max).

<Please insert Figure 1 about here>

Our analysis (specifically qualitative coding – Step 4 of our data analysis) revealed causal connections between uncertainty types where a distinct *root* uncertainty type gave rise to *symptomatic* uncertainty types. A frequent root uncertainty type was technical uncertainty. For example, in the system integration stage technical uncertainty (related to the need to update product designs and specifications) created relational uncertainty, evident in the information exchange and collaboration with suppliers needed to update technical drawings and models. Here technical uncertainty also caused resource uncertainty experienced in the lack of knowledge of new delivery times. The following e-mail exchange exemplifies this: E-mail from case company to supplier: *"There is a [component] missing I have learnt from the site. And I can also not find it in your drawings. Can you help?"* Response from supplier: *"It has been shown that the [components] are not made of [specified material]. Several [components] are located near a [structure] and in my calculations I assumed that the [components] are mounted on these nearby [structures]. We can (if there is room) put new [structures] in. (…) Shall we design the [new structures]?"* Response from case company: *"Many [components] are so [different from the specifications that they cannot handle such big (…) loads. (…) Yes, we need to organise these [new structures]."* This need to re-design components and product assemblies led to changes in the project schedule during the system integration and construction stages. Table 4 summarises the results regarding the perceived uncertainty types.

<Please insert Table 4 about here>

A number of other connections emerged from our analysis (specifically the qualitative coding in Step 4 of our data analysis). For example, we observed a snowball effect where a single root uncertainty type (technical uncertainty) propagated into two symptomatic uncertainty types (relational and organisational uncertainty). The following e-mail illustrates this: *"At a consortium meeting at the beginning of the year, we agreed that regarding [a product assembly] which was not fully defined yet. (…) The agreement was that the easiest solution to the problem [of lacking technical specifications] was that the [control system] was to be updated with new limits and instruments by [the case company]. We take over the instruments from [the supplier] on site. However, this update has not happened."* This issue created the need for internal alignment as well as further coordination with the supplier. As a result of this exemplar connection between uncertainty types, the case company missed their chance to get a bonus payment. Table 5 depicts the observed sequential interactions between uncertainty types.

<Please include Table 5 about here>

V. Discussion and conclusions

A. Key research insights

Current uncertainty theory describes *level of uncertainty* through *uncertainty multiplicity*, and its gradual reduction over the progression of a project via *uncertainty resolution*. Based on this understanding, this research aimed to investigate the development of uncertainty over the progression of a complex engineering project.

In line with prior theory we observed high levels of uncertainty in the early project stages, compounded of uncertainty multiplicity associated with multiple uncertainty types [2], [4], [29], [30]. In addition to the uncertainty types described by O'Connor and Rice [2], we observed a new type in complex engineering: *relational uncertainty*. Relational uncertainty has been previously described in the inter-organisational relationships [60] and is defined as the inability to predict and explain the actions of an external partner contributing to the complex product-development process, due to a lack of knowledge about their abilities and intentions. Our observations robustly connect to prior theoretical and empirical insights associated with static descriptions of uncertainty. However, we also observed a number of dynamic features in our data, in particular a u-shaped level of uncertainty curve, which are in explicitly contradiction to the prior assumption that gradual reduction via uncertainty resolution is the major driver of development of uncertainty, and thus cannot be explained via prior theory. This forms the basis for our major insight.

We identify a new mechanism affecting the development of uncertainty over project progression, acting in opposition to *uncertainty resolution*. We call this new mechanism ***uncertainty masking*** and define it as: *the process through which a 'root uncertainty' type is misidentified by the project team, resulting in the 'creation' and management of a 'symptomatic uncertainty' type*. Uncertainty masking has three important properties.

1. The root uncertainty that is the source of the misidentification does not 'disappear' when the symptomatic uncertainty is generated.

2. Management activities typically target and resolve symptomatic uncertainty types, which do not necessarily resolve the root uncertainty.
3. Following the above properties, root uncertainty type and symptomatic uncertainty types compound, driving the creation of even more symptomatic uncertainty in a positive feedback loop.

We directly observe these effects in our findings and are able to explain three key features of the data, not explicable via uncertainty resolution alone via our proposed uncertainty masking mechanism. First, we observed a large number of examples where a root uncertainty generated symptomatic uncertainty via misidentification. Here symptomatic uncertainty added to the overall level of uncertainty in the complex engineering project. For example, the project consisted of organisational uncertainty (e.g. internal organisation of technical offers from suppliers) *in addition* to its root of technical uncertainty. Importantly, in each case, the root uncertainty remained, illustrating the first proposed property of uncertainty masking. Table 5 provides three main examples of how this process occurred. The case findings show uncertainty masking associated with all uncertainty types; however, most notable was misidentification of technical uncertainty (e.g. technical specifications of a component) as other uncertainty types such as organisational uncertainty (e.g. internal organisation of technical offers from suppliers). Thus, there appears to be a positive link between the high degree of uncertainty multiplicity and uncertainty masking.

Second, we observed how resolution of symptomatic uncertainties did not necessarily result in the resolution of the root uncertainty, illustrating the second proposed property of uncertainty masking. Specifically, uncertainty resolution project activities were rendered ineffective because they targeted symptomatic uncertainty types instead of the root. Our findings showed that symptomatic uncertainty types often disappeared and reappeared over time as the case company resolved them without resolving the root uncertainty type. This was shown particularly with regard to technical uncertainty, which was important throughout the case project but was only treated by its symptoms in other uncertainty types (e.g. organisational uncertainty or relational uncertainty). This means that some response mechanisms were ineffective in reducing uncertainty and progressing the project tasks. Thus, uncertainty masking appears to have a substantial negative interaction with uncertainty resolution.

Third, the interaction between these two effects resulted in an increasing number of symptomatic uncertainty types as the project progressed, illustrating the third proposed property of uncertainty masking. Further to this general increase, we also observed increased complexity of the root – symptom interactions as the project went on, with more snowballing and chain type examples being observed (Table 5). This was related to the lack of resolving root uncertainty, leaving symptomatic uncertainty to re-appear through layering, chain, and snowball effects. For example, technical uncertainty (root uncertainty in early project stages) reappeared during system integration and construction where design details needed to be changed, resulting in re-definition of relationships with suppliers or internal re-development. Ultimately this further reduced the effectiveness of uncertainty resolution and created a compounding effect with respect to the overall level of uncertainty.

The explanatory value of uncertainty masking is strikingly illustrated by the observed u-shaped level of uncertainty curve. While existing theory can explain the initial reduction of uncertainty in early project stages, it cannot account for the observed growth of uncertainty in later stages. Here, uncertainty masking offers a new concept with which these observations can be explained. The three properties of uncertainty masking explained in this section created a positive feedback loop of uncertainty growth and resolution ineffectiveness, resulting in high levels of uncertainty in later project stages. Figure 2 illustrates the impact of this mechanism on the level of uncertainty across the progression of the project. This adds to uncertainty theory and offers a substantial new insight into how level of uncertainty, uncertainty multiplicity, and uncertainty resolution develop and interact over the progression of a project.

<Please insert Figure 2 about here>

B. Implications for research and practice

This research contributes to the engineering-management literature by offering an in-depth analysis of the dynamic development of uncertainty in complex engineering. We identified uncertainty masking as a key mechanism, which substantially expands current understanding with respect to the development of uncertainty over time. Uncertainty masking offers significant explanatory power for management theory and practice. It enables an explanation of *uncertainty growth* based on the joint effect of compounding root and symptomatic uncertainty as well as hampering uncertainty resolution. It also challenges underlying assumptions of current theory that presume that companies can identify the uncertainty types they face correctly and subsequently respond to them with suitable project activities, leading to reduction of uncertainty over time [2], [3], [5], [6], [25], [26]. As such, this research expands the discussion of uncertainty as a driving force in engineering projects.

This research has important managerial implications. Managers need to be able to correctly identify the uncertainty types their engineering project face. Specifically in complex engineering, this may be a significant challenge as shown by this research. For example, technical uncertainty may be misidentified by the project team because it creates challenges for supplier management or internal organisation. However, identifying uncertainty types correctly reduces the potential adverse effects of uncertainty in the later project stages, where the project team can deliver and integrating engineering outputs instead of re-designing and re-developing technical parts.

C. Limitations and future work

Three main limitations apply to the presented insights. First, case study research has been associated with observer bias and subjectivity [41]. This was mitigated by applying content analysis using a dictionary that offered a rigorous and reproducible data with a high degree of reliability [50], [52]. Second, content analysis via dictionaries has been criticised for possibly underestimating the importance of a concept because different terms may not represent the concept equally [51]. This was mitigated by considering the aggregate results from the entirety of the dictionary rather than interpreting the occurrence of specific terms. Further, the dictionary and use of specific terms in context was validated on a sample of the analysed e-mail corpus. Together, these mitigations ensured validity, and highlight the robustness of the findings [52]. Third, this research is based on insights from a single case. While this enabled us to provide in-depth evidence to answer our research question [41], this approach limits statistical generalisability [47].

This research points towards three important areas for further work. First, further work needs to investigate uncertainty masking and its effects on engineering management in more detail. This paper offers an initial proposition of uncertainty masking and its major properties as well as an explanation of its potential importance to engineering-management theory and practice. Further research, including other cases in different industrial sectors could facilitate testing of the specific properties proposed here, as well as further elaboration of the interactions between uncertainty masking and uncertainty multiplicity/uncertainty resolution. Second, further research needs to enable engineering manages in correctly identifying uncertainty types as well as in identify root uncertainties, calling for more behavioural investigations into uncertainty perception in engineering management. Existing theories assume managers ability to correctly identify uncertainty types. Our research however suggests that this is not always the case and misidentification and the compounding effect of symptomatic uncertainties can create significant adverse effects. Third, further work is needed to identify suitable management activities for specific uncertainty types as well as how to more effectively address root verses symptomatic uncertainties, enabling the development of causal response mechanisms. This would provide important insights for engineering manages and guide their choice of management activities in complex engineering.

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Tables and Figures

Table 1: Uncertainty types in engineering management literature

Example studies	Empirical context	Level of uncertainty	Uncertainty type(s)
Jiyao et al. [4]	Fast development cycles, study in technology firms in US	Static with descriptions of projects of high and low levels of uncertainty	Market uncertainty: Market newness and market turbulence Technical uncertainty: technological novelty and technological turbulence
O'Connor and Rice [2]	Radical innovation	Focus on projects with high levels of uncertainty	Technical uncertainty Market uncertainty Organisational uncertainty Resource uncertainty
Zhang and Bhuiyan [29]	Product design, model-based investigation	Static description of projects with low levels of uncertainty	Technical uncertainty - Described as Information uncertainty regarding initial specifications
Song and Montoya-Weiss [8]	Incremental versus radical innovation	Description of different projects with high and low levels of uncertainty	Technical uncertainty Market uncertainty
Yao et al. [6]	Incremental versus radical innovation, model-based investigation	Description of different projects with high and low levels of uncertainty	Market uncertainty, described as economic uncertainty Technical uncertainty
Hultink et al. [10]	Information-processing mechanisms to cope with uncertainty in high-tech industries	Focus on projects with high levels of uncertainty	Market uncertainty
Sicotte and Bourgault [61]	Research and Development projects in Quebec, Canada	Description of different projects with high and low levels of uncertainty	Technical uncertainty Project uncertainty Market uncertainty fuzziness

Table 2: Description of the development process in four project stages

	Conceptual design	Detailed design	System integration	Construction
Level of project activities	System-level activities for whole power plant specifying product requirements	Component-level activities to design project assemblies based on clear specifications	System-level activities for integrating product parts and assemblies	System-level activities for building and commissioning the plant on customer site
Stakeholder involvement	Internal for setting-up operations and sub-system teams;	Coordination within specialised sub-teams based on product parts	Coordination between specialised sub-teams including	Coordination with on-site specialists for plant construction

	External for identifying suitable suppliers and partners	and assemblies. Each sub-team involved internal and relevant external partners	internal and external stakeholders	
Engagement with external project partners	Relational involvement of long-term partners and new potential suppliers through coordination.	Transactional interaction with suppliers to ensure delivery of specified product parts and assemblies	Relational involvement of suppliers and external partners to solve interaction issues between product parts resulting in, e.g. re-design of specific parts	Transactional involvement of external partners to ensure timely supply and compliance with regulations

Table 3: Four steps of data analysis

Step	Analysis activities	Output
1	Timeline sorting to obtain a number of comparable corpus segments. Each corpus segment should contain the same amount of emails	10 corpus segments structuring the whole email data set
2	Qualitative coding of emails regarding the predominant focus of the email communication	Three folders focusing on: • Resource • Organisational • Relational
3	Quantitative content analysis using uncertainty dictionary (see Table 4)	Quantitative measure of level of uncertainty within the three folders over the 10 corpus segments
4	Qualitative analysis of emails with high uncertainty count	Characteristics of uncertainty types and their development over time

Table 4: Uncertainty dictionary used for content analysis

uncertain*, risk*, confiden*, not confident, unconfident*, possible, chaos, speculat*, hesita*, diffident, equivoca*, unclear*, ambivalen*
complex, complicated, unknown, not known, don't know, ignor*, unrelia*, untrustworthy*, trustless, *istrustful, undepend*, debatabl*, doubt*, irregular*, incalculable
change*, (un)expect*, unstable, unreliable, (un)anticipate*, (un)foresee*, (un)predict*, inconsistent*, inconstant*
chanc*, percent, %, (im)probabl*, probability, Sensitivity analysis, Monte carlo, fifty-fifty, variation, vary*, volatile, approximately, (un)likely, inexact, fluctuat*
imprecis*, ambigu*, vague*, unsure*
ndetermin, not determined, unresolved, irresolut*, not resolved, pending, *ndeci*, tentative, unconfirm*

Table 4: Observations of uncertainty types in the case project

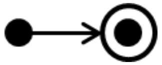
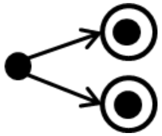
	Conceptual design	Detail design	System integration	Construction
Resource uncertainty	Clarifications regarding delivery time and quality, e.g. the following e-mail from a component supplier to the case company: “we have checked the points of your e-mail and we are able to confirm the points 2 and 3. Regarding point 1 [packaging the component with given requirement], we can pack them [using a different solution]. Please check if this is acceptable for you.”	Clarification on availability of specific connectivity between components, e.g. the following e-mail from a supplier to the case company: “What is the transport mechanism that transports [Component X] to the [Container]?” which resulted in a very short answer from the case company clarifying technical details.	Clarification on availability of specific components, e.g. the following e-mail from supplier to case company: “we have checked the status of your order with our manufacturing department and got the information that they have a delay, caused by delayed delivery of some purchased parts. The new scheduled date for delivery on site is [xx.xx.xxxx]. We apologize for the inconvenience.”	Ensuring availability of specific documents before and after part delivery on site. E.g. e-mail form supplier to case company: “thank you for signed shipping specification, but I still need [specific document] with your signature and stamp. You can find this document on my e-mail dated [date and time stamp]. Please sign, add date of delivery and stamp on bottom right corner of this [document] and send me back.”
Relational uncertainty	Clarification of regulatory and other requirements with the client, e.g. the following internal e-mail exchange based on conversations with the client: “Please see below an e-mail received from [the Client] in respect of the safety implications of [a component]. Please could you advise a date when the consortium expect to have installed and	Update on design progress with suppliers, E.g. the following e-mail from the case company to a supplier: “I plan to visit you next week to see the first [assembly] and how you are doing. (…) how will that fit into your plans?”	Need for information sharing regarding changes in specifications due to integration issues with integration with other components, e.g. e-mail from supplier to case company: “I expected to have the calculations by last Monday but unfortunately you have to wait until tomorrow afternoon, I'm constantly being pulled in by other projects.” Negotiations starting with suppliers and project partners	Clarification of technical specifications for component production, E.g. e-mail from a supplier to the case company “we had some issues with [the measurements of a component]. The [final component] ends up with a distortion. May we supply [different measurements of the component]? (…) Please let me know if it is suitable for you.” With the following response from the case company: “I’m sorry but it is not as simple as that. What if we

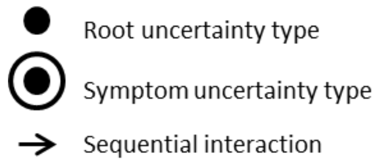
	commissioned the [component]?”		regarding delivery of components and product parts, payment of invoices, e.g. the following e-mail from a supplier to the case company: “our site team have investigated the issue and we also discussed the point in the site quality meeting with you. However neither party can find out how the problem occurred. Therefore I request the closure of the [issue].”	do [the following measurements]?””
Organisational uncertainty	Internal evaluation of technical offer from a component supplier. E.g. the following final e-mail from internal thread: “The offer looks fine from a process perspective. They have a comment about the frequency of [specific parts movements] that we will comment on.”	Internal exchange of information regarding technical details of component designs. E.g. the following e-mail exchange: “The 70 to 80% [component] and remaining preliminary drawings are to be sent today. These were last promised documents for [Supplier x] to be shipped on Monday. I am sorry we cannot wait anymore. [Supplier x] has been requesting these drawings [for a long time now]. We also need a schedule of when the entire [system] is complete. Please confirm.”	Internal alignment between component sub-teams based on technical interactions between components. E.g. the following e-mail from an internal e-mail thread: “You can lift vertically (almost) with max. [X load]. We assume that your team themselves have an agreement regarding the component requirements. What you have there in the drawing weighs [more]” Response from linked component team: “To make sure there are no doubts about the items and their location, I have attached a drawing of the module with the instructions. I would like to confirm whether it is possible to	Internal alignment and information exchange to solve a technical problem and deal with specific supplier deliveries, e.g. the following internal e-mail clarified a long-standing (but ignored issue regarding a specific component: “At a consortium meeting at the beginning of the year, I made an agreement on [Component x] which was not [fully to specifications]. (…) The agreement at the consortium meeting was that the easiest solution was that the drawings would be updated with the new [technical specifications] and these specifications would be moved to [the case company’s] drawing. However, this update has not

			charge the benefits." Response: "Yes, it is ok to lift [the component] as shown."	happened." This issue led to some e-mail exchange with Supplier A and the plant site, leading to changes in the project schedule.
Technical uncertainty	Concerning technical specifications of components and product parts, E.g. the following e-mail from Supplier B to case company: "It has been shown that the [component] has not been drawn in their exact coordinates. Several of the [components] are located near a [structure] (…) in the calculation model I assumed that the [components] were hung up in these nearby [structures]. If we have to fit in, we can (if there is room) put new [structures] under two others."	Clarification regarding technical specification and effects of placing specific components within a sub-system. E.g. e-mail from supplier to case company: "if you build [Components A and B to the given specification], that's no problem. If you place a filter where you suggest, this would give a significant (…) risk of [extensive wear]."	Changes to technical specifications due to interdependencies between sub-systems. E.g. E-mail from case company to supplier: "from [internal department] I have been told that due to the weight of [Component P] and the momentum, it has been necessary to build in a (…) system to [change the component behaviour]. This matter we will have to discuss once I have received the arrangement drawing. Please come back at the earliest."	Compliance with technical regulations and safety specification, e.g. the following internal e-mail: "the appropriate safety integrity levels (SIL) shall be identified according to [international standard]. The SIL levels are implemented as follows: (…) The [Component T] limiter as part of the safety integrity functions should have been realized as SIL [Level x], [Case company] has selected to purchase a [Component T] classed as SIL [Level 3]. [Specification of technical measurements on site]"
Additional observations of sequential interactions	Sequential interactions in terms of mutations between a root uncertainty type and a symptomatic uncertainty type; Example: technical uncertainty (technical specifications of a component) leading to organisational uncertainty (internal organisation of technical offers from suppliers)	Very few sequential interactions in terms of mutations between a root uncertainty type and a symptomatic uncertainty type; Example: technical uncertainty (regarding angle between two components to allow material through flow) identified as resource uncertainty (clarification of production input and transport mechanism with supplier)	Many sequential interactions in terms of mutations and snowballs. Mutation example: resource uncertainty (delivery of wrong bolt size) identified as organisational uncertainty (need for internal clarification of requirements and change of technical specifications	Many sequential interactions in terms of mutations, snowballs and chains. Mutation example: technical uncertainty (material changes) identified as relational uncertainty (dispute with supplier over solution approach) Snowball example: technical uncertainty (component measurements) leading to

			Snowball example: technical uncertainty (technical changes due to integrating components) identified as resource uncertainty (new delivery time and ability to assemble) and relational uncertainty (need for information sharing with supplier on new technical specifications)	relational uncertainty (dispute with supplier over responsibility) and organisational uncertainty (need for internal identification of problem and solution) Chain example: Relational uncertainty (negotiation with supplier over mismatch of their component to connected components) arising from a disagreement during earlier product stages where technical uncertainty (unknown technical component specification because of dependence on connected components) created relational uncertainty (discussions with supplier regarding component specifications) and organisational uncertainty (agreement that case organisation would ensure fulfilment of fixed technical component specifications with connected components)

Table 5: Examples of symptomatic uncertainty in the case

Pattern	**Visualisation**	**Description**	**Case examples**
Layer		A root uncertainty type is misrepresented as a symptomatic uncertainty type.	Technical uncertainty creating Organisational uncertainty: changes in components specifications gives rise to identifying the internal responsibility for component re-design
Snowball		A root uncertainty type is misrepresented as multiple different symptomatic uncertainty types.	Technical uncertainty creating resource uncertainty and relational uncertainty: Integration between components in systems integration stage created need for coordination with a supplier to update their component and deliver this new component to the site.
Chain		A root uncertainty type is misrepresented as a symptomatic uncertainty type, which is in turn misrepresented as a different symptomatic uncertainty type.	Technical uncertainty created relational uncertainty, which was resolved via creating organisational uncertainty: Unknown specifications of a technical component required by s supplier and the case organisation created discussions with the supplier. This led to an agreement between supplier and case organisation to base the supplier's assembly design on specific assumptions, which the case organisation would ensure to adhere to in connected product parts. This, however, was not done which gave rise to relational uncertainty at the construction stage with the supplier where the original agreement was re-visited and subsequently required re-design of the connected component and internal alignment in the case company. As a result of the change in the original schedule, the case company did not receive a bonus payment.



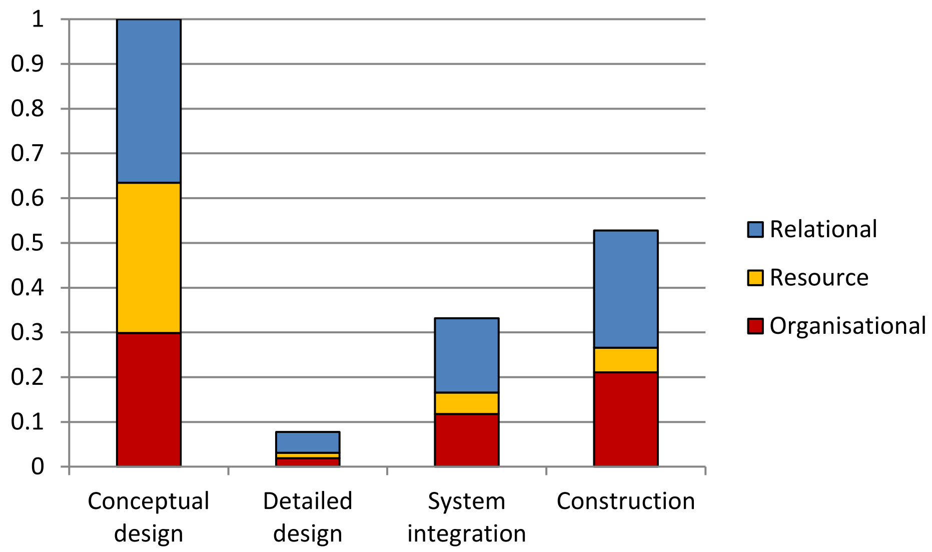


Figure 1: Uncertainty over time

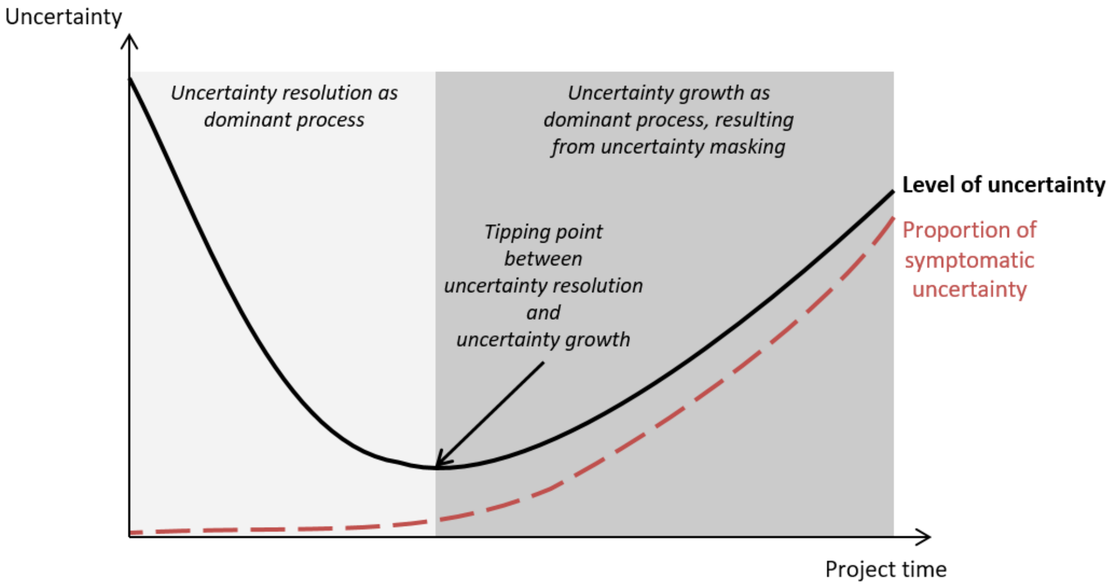


Figure 2: Schematic representation linking uncertainty multiplicity, uncertainty masking and level of uncertainty

Dynamism in complex engineering: explaining uncertainty growth through uncertainty masking

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