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Uncertainty and activity selection in new product development: An experimental study

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Abstract

Uncertainty drives project activity in New Product Development (NPD), and its resolution is crucial to project performance. However, there is a major gap in understanding the causal links between different uncertainty types and the project activities they trigger. Engineering managers lack guidance on how best to respond to different uncertainty types. We close this gap by experimentally contrasting responses to two uncertainty types central to NPD: technical and organizational uncertainty. We describe responses with respect to core engineering project activities: representation, information, and knowledge sharing. We present evidence from an experiment involving 50 professionals and 74 master's students. The results show that uncertainty type has a significant effect on activity response, and that there is a significant ordering effect within this response. Based on the identification of a new response type, change of situation, our findings show that technical uncertainty drives change of situation and representation activity,

while organizational uncertainty drives information and knowledge sharing activities. This provides the basis for three main contributions. First, we identify "*change of situation*" as a new type of response to uncertainty in NPD. Second, we describe different responses to technical and organisational uncertainty. Third, we characterize an ordering effect in responses to uncertainty.

Managerial relevance statement

This research offers important advice to managers of NPD projects in practice. First, NPD managers are advised to understand the uncertainty type they face and then identify a suitable response in terms of project activity. For technical uncertainty, typical responses include representation activities (e.g. prototyping or simulation) and changes to the situation. For organizational uncertainty, responses include information and knowledge sharing activities to enable the NPD team to reduce this uncertainty type and progress in the NPD task. Second, these responses to uncertainty can be combined to offer a more substantive approach for reducing uncertainty. For example, for technical uncertainty managers could consider varying the constraints of a problem by changes in situation to allow more effective representation activity. Similarly, for organizational uncertainty knowledge sharing could be followed by subsequent changes in situation to adapt the project goals and scope based on the discovered information. Planning for such combinatory responses would enable NPD managers to better tailor their response to the relevant uncertainty type and thus more effectively allocate time and resources when responding to uncertainty.

Keywords: uncertainty, activity selection, new product development, innovation

I. Introduction

Uncertainty is one of the major challenges faced in engineering management [1]–[3]. Uncertainty can adversely affect project activities and decision making during Research and Development and New Product Development (NPD) [4]–[7]. Kreye et al. [8] define uncertainty as the "*potential deficiency in any phase or activity of the process which can be characterized as not definite, not known or not reliable*" (p.683). Critically, NPD team's perceive this uncertainty and subsequently act based on this situational experience [9], [10], shaping the direction of the NPD project. Thus, it is essential to understand how best to deal with uncertainty in a given situation.

Uncertainty in NPD projects, particularly in the engineering management context [11]–[13], cannot be treated as a single construct, rather it is decomposed into numerous types [9], [14]. Each type is perceived differently by individuals, who subsequently react in different ways [15], [16]. Thus, uncertainty type is critically related to the project activities undertaken by a team [17], [18]. However, while uncertainty is linked to project activity [19] and some studies highlight the potential effect of uncertainty type [9], [20], specific causal links have not been established.

Most important for engineering management is the distinction between technical uncertainty i.e. the degree to which the technical knowledge of the product is understood and realizable [9], and organizational uncertainty i.e. the gap between the organization's capabilities and needs [21]. Specifically, NPD projects often face significant challenges that involve both technical and organizational aspects [3], [22], [23]. For example, Wasiak et al. [24] highlight the joint importance of organizational and product focused communication, as well as their interaction in NPD.

Current research acknowledges the impact of uncertainty on project activities and the subsequent link between uncertainty resolution and project performance [19], [23], [25]. For example, technical uncertainty has been linked to both information seeking [26] to resolve lack of

knowledge in the fuzzy front end [17], as well as knowledge sharing with the NPD team [27]. However, these links are not consistent across studies. Further, the impact of organizational uncertainty on project activity has thus far only been generally described [28]–[30]. Thus, current research lacks conclusive evidence on the different uncertainty types as drivers of specific project activities.

This gap is a critical block to further theory development as well as efforts to provide more tailored managerial support. To address this, we answer the following research question: *What are the links between technical and organizational uncertainty and project activities in NPD*? We present insights from an experimental study with practitioners and Master's students. Our findings suggest that technical uncertainty drives change of situation (identified in this research) and representation activities, while organizational uncertainty drives information and knowledge sharing activities. The results provide the basis for a number of contributions. This research contributes to NPD theory by linking uncertainty types to specific project activities and enabling significant improvements of managerial practice.

II. Theoretical background

An NPD project can be defined as a set of activities aimed at (re-)developing a product or establishing the base for the generation of innovative products [31]–[33]. NPD projects involve multidisciplinary processes [9], [27] and cross functional cooperation between different departments [24], [34]. This creates complexity and undetected interrelations between project elements [35], and subsequently, high levels of uncertainty [36]. As such, uncertainty is a critical aspect of NPD [37], [38] and can significantly impact project outcome both positively and negatively. Positive effects include unexpected opportunities emerging during the innovation process [37], [39], while negative effects include managers' reduced ability to make decisions and

enact planned project activities [40]. Thus, current research describes an overall relationship between uncertainty and project activity in NPD [41].

A. Uncertainty in engineering NPD

Uncertainty can have critical adverse effects on mangers' and teams' abilities to make decisions and complete NPD activities [4]–[7]. For example, when individuals are uncertain about the problem and task due to the complexity of the technology involved, they are less able to map the implications of their actions [12]. Similarly, when individuals are uncertain about technical scope and customer needs, they are less able to decide on the key functional characteristics of the product [42]. Further, complex products with long life spans [43], where interdependencies between the operational environment and future technologies are difficult, if not impossible, to predict, reduce individual's ability to make good decisions about how the project should progress [44]. As such, uncertainty is an important factor in NPD. In line with this, significant contributions have been made to describing and studying uncertainty. Various uncertainty types have been distinguished, based on the specific source, including: organizational, technical, market, resource, environmental, and relational [9], [14]. Of these uncertainty types, technical and organizational uncertainty have been highlighted as particularly critical and relevant for NPD [24], [34], [45]. We thus aim to study these two uncertainty types in more detail.

Technical uncertainty is defined as lack of understanding of the technical knowledge underlying the new product and its transformation into an output [9]. Technical uncertainty is a major issue in the early NPD stages [7], [9], [46] when the technology is rudimentary, unfinished, ambiguous, fragile and expensive [47]. Technical uncertainty is related to the product and its characteristics, with managers linking it to problems related to the novelty of the technology [9].

Organizational uncertainty is defined as the gap between the capabilities possessed by the organization and the capabilities needed by the organization [21]. This uncertainty type can be connected to the project process [30] and the organization's internal procedures, such as NPD project processes, schedule and budget [29]. Organizational uncertainty can arise from changes that occur in the project, such as change of project manager or changed project priority within the organization, with managers linking it to issues related to hierarchy and availability of finance [9]. Both of these uncertainty types are prominent in engineering management [3], [22], [23], and have distinctly different properties. While prior research has described various responses to these uncertainty types [9], [48], the specific differences in causal links to different project activities have not been identified or described.

B. Project activities in NPD

Activities describe specific, observable patterns of behavior directed towards achieving a goal [49], [50]. Thus, the combination of individual's activities describe the work undertaken in a team [51], [52]. This combination can be conceptualized as 'project activities', which are defined with respect to the predominant individual-scale activities enacted by project team members [51].

During NPD, project team members perform a wide range of activities in order to reduce or manage uncertainty, with effective selection being crucial to project performance [41], [53], [54]. For example, technical uncertainty associated with a novel solution idea, might trigger the team to better understand the idea and its potential in relation to the project. Typical responses here might include information seeking to improve the NPD team's knowledge of the scientific underpinnings of the technological development [26]. However, these overall tasks can be more fundamentally classified with respect to the basic actions that they are made up of [49], [50]. Here, three basic groupings have been proposed in the engineering design context [18], that are

relevant for NPD [51] and have been explicitly linked to uncertainty [41]: information activity, knowledge sharing activity, and representation activity.

Information activity is defined as the manipulation of objective data to improve processes or outcomes [19] and is related to gathering, processing and archiving data [55]–[58]. Information activities refer to data processing detached from human belief judgements [59], [60]. Information activities reduce managers' and engineers' uncertainty by providing objective data in response to specific challenges [58].

Knowledge sharing activity refers to exchange shaped by human beliefs [61], [62], and occurs predominantly as interactions in a project team. Here, individuals exchange and integrate knowledge according to their understanding and beliefs [19]. Examples of knowledge sharing activities are meetings and training [5], [19], [58]. Knowledge sharing activities reduce managers' and engineers' uncertainty by developing a shared understanding of, for example, aims and challenges [19].

Representation activity describes practices where individuals externalize their understanding [63], often with respect to product elements. Representation activities include simulations, prototyping and mock-ups [64]. Such representations are typically used to test and learn [31], especially in conditions of high technical uncertainty [65]. In addition, representation allows a (virtual) realization of ideas and a visualization of the technical feasibility of a new product before it is launched [17], [65]. Representation reduces managers' and engineers' uncertainty by increasing understanding of the product elements and their potential interactions [66], [67].

C. The link between uncertainty and activity selection

Although there is a lack of theorizing about the link between the specific uncertainty types and the project activities described above, some potential links can be identified from the broader

literature. For example, rough prototypes (i.e., representation activity) have been described as useful for reducing technical uncertainty in the fuzzy front end [17]. Also, in a study of NPD effectiveness technical uncertainty has been described as related to prototype development proficiency [68]. However, technical uncertainty has also been connected to information [26], and knowledge sharing activities [27], as well as organizational decision making [46]. As such, the causal link between technical uncertainty and representation activity is not clear. Similarly, relationships between organizational uncertainty and a wide range of activities have been described [28]–[30] but specific causal links have not been tightly defined or evaluated with respect to specific project activities.

We aim to fill this gap by investigating the links between two uncertainty types and project activities in NPD. The lack of theory on uncertainty as a driver of specific project activities means that we were unable to define meaningful hypotheses. We thus adopt an inductive approach based on a strong conceptual framework grounded in the literature. We conceptualize the two uncertainty types as technical and organizational uncertainty. We conceptualize potential project activities initially as information activity [19], knowledge sharing activity [61], [62] and representation activity [63].

III. Methodology

To answer our research question, we carried out an exploratory quasi-experimental study, which contrasted responses to technical and organizational uncertainty described in a number of scenarios. This approach is appropriate for two main reasons. First, experimental studies allow for the evaluation of specific links between variables, the contrast between different inputs [69], and the specific evaluation of verbal expression of uncertainty [73]. Second, scenarios provide a means for evaluating individual response to a specific situation [70]–[72].

A. Scenarios and experimental procedure

Six scenarios were created based on an overall framing as an internal NPD project. These were developed from literature as well as observations from a preliminary industrial study (comprising two engineering design cases in a high technology consumer goods company, with 45 interviews, observations, and secondary data). Three scenarios focused on technical uncertainty and three on organizational uncertainty. See the examples below (and the other four scenarios in the Appendix):

Technical uncertainty: "*One of the project tasks is to create a new battery which provides enough power for the phone to fully function for 72 hours. For this task, you are working with a new technology that you have never worked with before to develop a battery that is new to the market: smaller, thinner and more powerful. This new technology, however, is not developing as you expected: the battery life is not the estimated hours. Consensus in your team is that the technology is still under-developed but your team does not have the time to run all the tests that are needed to improve the battery. You need to make a decision regarding the next steps you and your team will take to address this challenge.*"

Organizational uncertainty: "*You are working according to a new product development process. This process has several gates, which define what deliverables need to be presented to the product manager. It is expected that the whole project moves from one gate to the next in a pre-defined schedule. However, the process is not equally advanced in all the departments. While Mechanics is working with mock-ups and is ready to present their deliverables for Gate 2; the battery team is not ready for simulations and needs more time. You need to make a decision regarding the next steps you and your team will take to address this challenge.*"

The scenarios were refined and revised iteratively, based on extensive testing with academic experts as well as with industry managers. In particular, this process validated that the uncertainty types highlighted in each scenario were perceived correctly i.e. technical uncertainty was perceived as such. This is important, because individuals act based on their perception of uncertainty, which deals with their experience of the situation i.e. their lack of understanding, confidence and certainty [8]. As such, perceived and extant uncertainty do not always align, hence each scenario was validated iteratively to ensure alignment. More generally, each iteration included feedback on clarity, complexity, experienced realism and narrative informativeness, following best practice for scenario development [71], [72], [74].

Based on these scenarios, participants were asked to follow the experimental procedure outlined in Figure 1. Participants first gave consent and read a general brief. They then read and responded to the six scenarios in turn. Participants responded by listing, in order of performance, the three activities that the team would undertake to deal with the described challenge (using open text input). Subsequently, they indicated how confident they were that the listed responses would help the team to resolve the problem using five-point Likert-type item(s) (not at all confident to very confident). Finally, demographic and other control data was gathered.

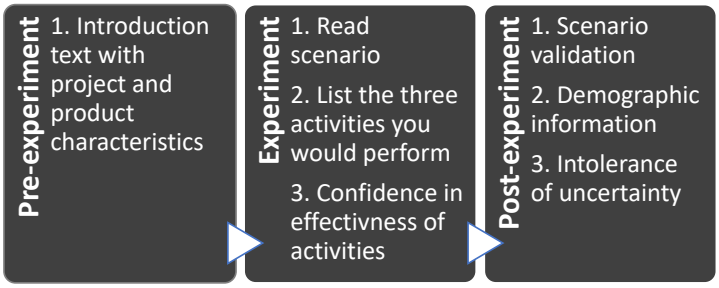

Figure 1 Experimental procedure

B. Sample

The experiment utilized two samples comprising students and professionals. A student sample was used to maximize internal validity (i.e. the extent to which evidence supports conclusions within the context of a specific study), due to their generally acknowledged superiority for diligently following complex study designs, and their overall homogeneity [75]. A professional sample was used to maximize external validly (i.e. the extent to which conclusions this specific study apply to other contexts, particularly in practice)[76]. Together the two samples balance internal and external validity concerns, whilst improving statistical validity, following best practice for sampling design [76], [77].

Sample 1 comprised 74 students enrolled in a Design and Innovation Master's degree at a technical university in Scandinavia. The experiment was introduced in a classroom setting, using Qualtrics software with paper alternatives (in case of lack of computer access). Sample 2 comprised 50 engineering management professionals, including project managers, product managers and team leaders; they responded using Qualtrics software. To support generalisability and the representativeness of the sample, professional participants were selected based on the following criteria, in addition to the engineering management focus and roles stated above: all belonged to teams of at least five individuals, in companies employing more than 10 people. These criteria were based on the fact that the problems experienced by very small companies differ substantially from those experienced by more usual engineering NPD teams [78], [79]. The characteristics of both samples are presented in Table 1.

Table 1: Sample characterization

	Age				**Gender**	
	under 18	**18-24**	**25 -34**	**35 older**	**Male**	**Female**
Students (total 74)	19%	48%	33%	0%	68%	32%
Professionals (total 50)	0%	12%	42%	46%	76%	24%

C. Data analysis

Data were analyzed in two steps. First, all responses were coded with respect to the project activities described by the participants. Open coding was used to identify the main categories, followed by axial coding to relate the categories to their subcategories [80]. A coding scheme was developed in an iterative process [81]. Our conceptual framing of project activities was used as the starting point and was elaborated based on concepts that emerged. An emerging code was "*change of situation*", which could not be integrated in the previously conceptualized project activities. This was inductively identified from the participants' responses and was not explicitly probed for in the design of the experiment. Specifically, participants were asked to "*List the first three activities your team would take to deal with this challenge*" for each scenario. Change of situation was identified based on its nature as a decision to change something, with no associated time-span; this is in contrast to activities, which describe specific actions with a distinct time-span. For example, 'allocate more time' is a simple decision point while 'search for information' implies a goal directed task over a period of time. Descriptions in the data coded as change of situation included 'making a decision as to the technical specifications of the product' and 'changing the time plan'. While changes of situation were directed towards various aspects of NPD including the conditions, context and objectives, we did not further sub-divide the coding for two main reasons. First, while change of situation could be reliably identified from the data, specific sub-divisions associated with, for example, locus of control or specific focus, were often less clear. For example, 'allocate more resources' could refer to project internal or project external resources. Similarly, 'change the time plan' could refer to changes within the project structure or changes to the overall project timeframe. As such, the selected level was appropriate for consistent identification and inter-coder reliability. Second, the lack of decomposition makes change of situation parable with

the other activities, which were also evaluated at an overall level. The data were coded by two researchers to check inter-code reliability [82]. The final coding schema is summarized in Table 2, together with a number of examples for each code.

Table 2: Coding scheme with examples

Activity	Definition	Operationalization
Information	Information activity is defined as the exploitation of objective data to improve processes or outcomes and is related to gathering, processing, and archiving.	Activities related to: seeking data, processing data, evaluate information, not shaped by beliefs
Examples	*"Research to improve the product" / "Search for other products" / "Read about the problem" / "List the most important tests" / "Research the costing"*	
Knowledge Sharing	Knowledge sharing activity refers to interactions between individuals where they exchange knowledge expressed with respect to understanding and beliefs	Activities related to: sharing knowledge/understanding, integration, shaped by beliefs
Examples	*"Facilitate discussion between all involved parts" / "Get groups together to get a clear picture" / "Discuss with the team" / "Brainstorm" / "Get the team to suggest alternatives"*	
Representation	Representation activity describes practices by which individuals' externalize their understanding, for example, test and learn about product elements.	Activities related to: development of the product, prototyping/testing, creation activities
Examples	*"Test the solutions" / "Make a prototype" / "Simulate the problem" / "Try alternative solutions" / "Test other products"*	
'Change of situation'	An individual seeks to change the parameters of the situation e.g. the conditions, context or objectives	Related to changes in: management, planning, resources
Examples	*"Create a new time schedule" / "Give more time" / "Put the project on hold" / "Reallocate staff or resources within the team" / "Refocus the whole team on the problem"*	

Second, all codes were transformed into categorical variables to enable content analysis. This allowed for quantitative evaluation of category frequency and prioritization [83](Response position 1, 2 and 3). This frequency count was calculated for each scenario based on the three response positions, and thus ranges from 0 to 3. The average was then calculated for each set of scenarios (technical verses organizational uncertainty). Given the nature of the data, throughout we followed best practice content analysis [84, pp. 359–360]. Hence, we use chi-squared tests to evaluate the effect of uncertainty type, and position within each uncertainty type, with the null hypothesis of no effect. These were used to establish differences between responses to technical and organizational uncertainty, overall and in terms of the priority among responses. Further, this helps to explain i) which response was most frequently linked to each uncertainty type overall

(compared to the other responses); ii) which response was most frequently linked to each uncertainty type in each response position (1, 2 or 3) (compared to the other responses); iii) if there were differences in response frequency between each response position; iv) if these variables differed for responses to technical versus organizational uncertainty. All tests were carried out on Sample 1 and 2 separately as well as both samples in total.

D. Robustness checks

To check robustness, additional questions were added to the end of the study (post-experiment in Figure 1). Here, in addition to demographic data, and evaluation of uncertainty intolerance [85], participants were asked to rate scenario similarity in terms of: complexity, composition, realism ("*while I was reading the scenarios, I could easily image the situation taking place*."), transference ("*I could picture myself in the situation described in the scenarios*."), informativeness , confidence about their decisions, clarity and complexity; all using a five-point Likert scale (strongly disagree to strongly agree). Based on these variables we ran several regression models and correlations. No systematic differences were found between scenarios or uncertainty types in either sample, and none of the control variables had a significant influence on the results. Further, results from the two samples were systematically compared via chi-squared tests. This revealed that there were no significant differences between the responses in the two samples (technical uncertainty $X^2 = 5.59$ $p > 0.1$; organization uncertainty chi-squared = 0.91 $p > 0.1$). Similarly, we compared results from within the different demographics represented in the professional sample related to experience. Again, no significant differences were found.

IV. Results

Analyzing the results initially as an aggregated total (i.e. across all three response positions), shows a significant difference between technical uncertainty and organizational uncertainty ($X^2 = 86.57$ p

< 0.000). Figure 2 shows the different response profiles for the two uncertainty types illustrating how each uncertainty type has a specific effect on activity response. Further, Table 3 summarizes the differences in mean response to the two uncertainty types for each response position. Together these results enable us to derive general links between uncertainty type and response to technical uncertainty (detailed in Section A) and organizational uncertainty (detailed in Section B).

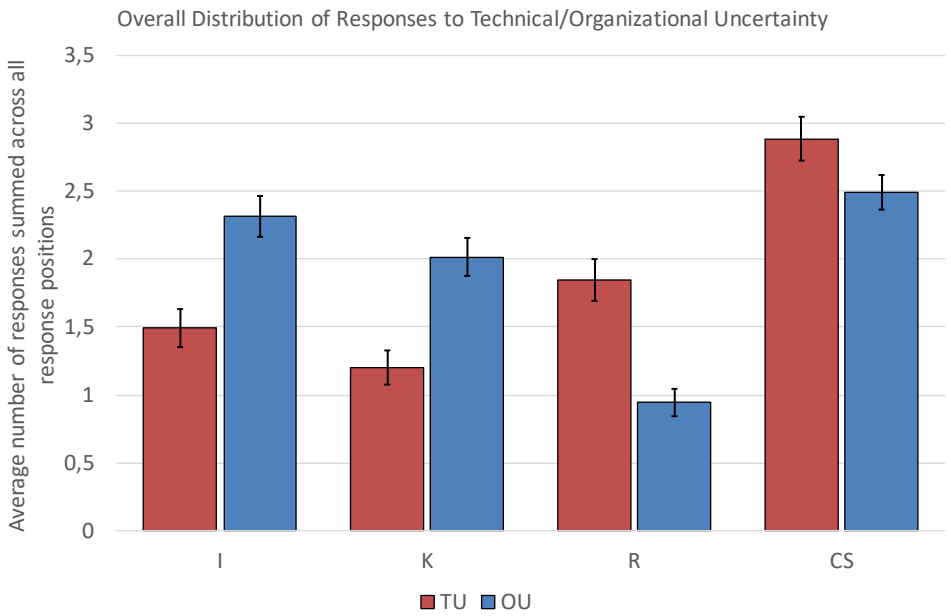

Figure 2 Overall responses to technical/organizational uncertainty (TU/OU) with standard error bars: information (I), knowledge sharing (K) representation (R), change of situation (CS)

Table 3: Differences between mean responses to Technical and Organizational Uncertainty

Activity	**1st Position**				**2nd Position**				**3rd Position**			
	Information	**Knowledge sharing**	**Representation**	**Change of situation**	**Information**	**Knowledge sharing**	**Representation**	**Change of situation**	**Information**	**Knowledge sharing**	**Representation**	**Change of situation**
Student	-0.30	-0.45	0.20	0.50	-0.27	-0.19	0.32	0.04	-0.19	-0.12	0.47	-0.37
Professional	-0.38	-0.16	0.10	0.30	-0.20	-0.52	0.34	0.22	-0.34	-0.22	0.32	0.20
Total	-0.33	-0.33	0.16	0.42	-0.24	-0.32	0.33	0.11	-0.25	-0.16	0.41	-0.14

A. Technical uncertainty

Technical uncertainty drives change of situation (CS) and representation (R), across all three response positions as illustrated in Figure 3a. Examples of CS include *"find time to make the tests",*

"push the deadline", "redefine the scope" and "assign temporary resources" and of representation include "*rapid prototyping*", "*test", "remake the battery"* and *"make more tests"*. This finding was observed for both samples separately and for the total sample.

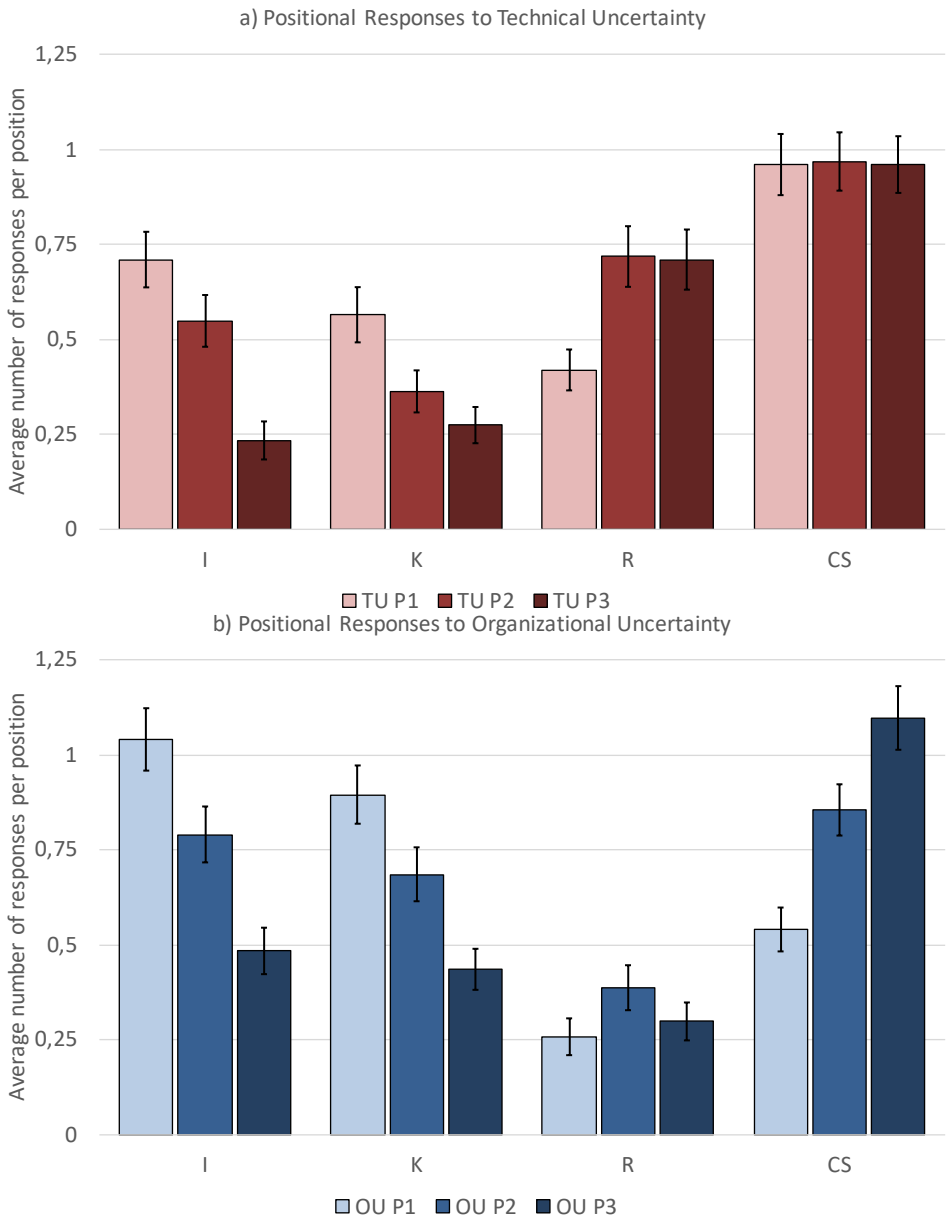

Figure 3 a) Response to technical uncertainty (TU), b) response to organizational uncertainty (OU), with standard error bars for response positions (P) 1-3: information (I), knowledge sharing (K) representation (R), change of situation (CS)

Emerging from the results was a dynamic development across the response positions (1-3). While CS was most frequently observed for all three response positions, we observed a dynamic

development of priority for the remaining three response types: while information activity was observed to be the second-most frequent response type for response position 1, its importance reduced for response position 2 and 3. At the same time, the importance of representation increased from response position 1 to response position 3. As such, position was found to have a significant effect on response to technical uncertainty ($X^2 = 48.63$ $p < 0.000$). This suggests an ordering effect with regard to priority of responses over time, as initially CS was complemented with information activity, while at later response positions it was complemented with representation. Here ordering effect is defined as change in response type across the three response positions indicating a prioritization and structuring of activities. See Table 4 for a summary of means for all positions.

Table 4: Summary of position means for Technical and Organizational Uncertainty

Activity	**1st Position**				**2nd Position**				**3rd Position**			
	Information	**Knowledge sharing**	**Representation**	**Change of situation**	**Information**	**Knowledge sharing**	**Representation**	**Change of situation**	**Information**	**Knowledge sharing**	**Representation**	**Change of situation**
Technical Uncertainty												
Student	0.76	0.53	0.46	0.95	0.59	0.41	0.72	0.91	0.27	0.30	0.72	0.81
Professional	0.64	0.62	0.36	0.98	0.48	0.30	0.72	1.06	0.18	0.24	0.70	1.18
Total	0.71	0.56	0.42	0.96	0.55	0.36	0.72	0.97	0.23	0.27	0.71	0.96
Organizational Uncertainty												
Student	1.05	0.97	0.26	0.45	0.87	0.60	0.39	0.87	0.460	0.42	0.24	1.18
Professional	1.02	0.78	0.26	0.68	0.68	0.82	0.38	0.84	0.52	0.46	0.38	0.98
Total	1.04	0.90	0.26	0.54	0.79	0.69	0.39	0.86	0.48	0.44	0.30	1.10

B. Organizational uncertainty

Organizational uncertainty drives change of situation (CS), information and knowledge sharing, as illustrated in Figure 3b. Examples of CS here are "*do a risk analysis"* and *"identify the effect on the project plan", "research"* and "*investigate what is the cause of the delay*". Aggregating all

responses shows that CS is more important than knowledge sharing and representation, but not information.

The findings further showed a dynamic development of project responses over the response positions, suggesting that the overall response to organizational uncertainty has a significant ordering effect ($X^2 = 67.57$ $p < 0.000$). Specifically, the values for information and knowledge sharing, which were second and third most frequent in response position 1, were lower in each subsequent response position. At the same time, CS gained in importance, being the most frequent in response position 3. See Table 4 for a summary of means for all positions. This suggests a sequential ordering effect of project responses to organizational uncertainty, where organizational uncertainty initially drives information and knowledge exchange activities to gather data for decision making. This then feeds into decisions to change the situation, for example "*set up new time frame for development"* and "*assign more resources"*.

V. Discussion

A. Key insights

This research provides three main findings. First, we identified a type of response to uncertainty not previously captured in discussions focused on project activity: "*change of situation*". Second, we found an overall link between specific uncertainty types and specific responses. In particular, we found a link between technical uncertainty, change of situation and representation activity. Furthermore, we found an overall link between organisational uncertainty, information activity and knowledge sharing activity. Third, our findings suggest patterns in the ordering of responses to specific uncertainty types. This section discusses these findings in light of the research question and current theory.

First, we identify 'change of situation' as a major component in the observed responses to uncertainty. We define change of situation as *decisions aimed at changing project boundary conditions, context and objectives to allow for an altered course of action*. For example, an NPD manager might attempt to change a project deadline, rather than continuing with a course of action that may no longer be feasible in light of the uncertainty. This is distinctly different from an activity response. While, activity describes observable patterns of behavior enacted over time and directed towards achieving a goal in a given context [49], [50], change of situation captures decisions to alter the goal or context. This is an important finding because uncertainty has not previously been identified as a distinct driver of decisions to change situation during the progression of the NPD project. Specifically, prior research has focused on activity as the primary response mechanism [18], [19], [86]. Despite this, deciding to change a situation to enable activity does correspond to some models of design work, where decisions are used to enable activity in the face of extensive unknowns [67], [87]. This suggests the need to reconceptualize the range of responses to uncertainty and develop response models that account for both activity and change of situation.

Second, we describe distinct links between uncertainty types and specific responses. In particular, we link technical uncertainty to change of situation and representation. Due to the breadth of previous descriptions linking technical uncertainty to project activities, our research partly confirms and partly contradicts existing works. Our research confirms prior descriptions linking representation and technical uncertainty [17], [31], [65]. This aligns with expectations regarding the specific nature of technical uncertainty, focusing on product functioning. However, our research did not confirm descriptions linking information activity [26] or knowledge sharing activity [27] and technical uncertainty. While our results did include these activities, they were not

significant in comparison to representation. Instead, our research highlights change of situation as a major response to technical uncertainty. In particular, these changes of situation focused on reducing the project scope or increasing the timeframe and resources available for testing. As such, there is a logical synergy between the perceived need for representation activity (primarily comprising time and resource intensive prototyping/testing) and change of situation (either reducing scope or increasing resources) to make this activity possible. Our research thus extends current theory by offering new insights on the overall responses to technical uncertainty in the form of representation activity and change of situation.

Further, we link organizational uncertainty to information and knowledge sharing activity. Due to the relative immaturity of the literature on organizational uncertainty in NPD (in comparison with technical uncertainty), our research offers one of the first empirical insights on the specific project activities driven by this uncertainty type. Importantly, we identify two main activities in comparison to prior descriptions that collectively highlight almost all types of response [28]–[30]. We thus extend current theory by, for the first time, specifying prototypical responses to organizational uncertainty.

Third, we identify distinct patterns in the ordering of responses depending on uncertainty type. Specifically, we identified two distinct ordering effects, which emerged from our data. The first ordering effect was based on priority, which we observed for technical uncertainty. Here, the second most important project response emerged as representation overall.

The second ordering effect was based on sequence, which we observed for technical uncertainty and organizational uncertainty. Here, our research showed that NPD managers initially react to technical uncertainty with change of situation complemented by information activity, which changes to change of situation complemented by representation activity. For organizational

uncertainty managers first engage in information and knowledge sharing activities together, while later engaging in only change of situation. We thus summarise the following response patterns for technical and organizational uncertainty.

Technical uncertainty → *change of situation and information activity* → *change of situation and representation activity*

Organizational uncertainty → *information and knowledge sharing activity* → *change of situation*

We illustrate the key insights from this work in Figure 4, which highlights the new type of response as well as the distinct ordering effects that differentiate technical and organizational uncertainty. In particular, this framework provides a basis for further evaluation of ordering and structure in response to uncertainty types. This extends prior descriptions that only characterize direct relationships between uncertainty type and project activity [9], [41]. To the authors' knowledge, no other works describe ordering patterns in responses to uncertainty. Thus, our results substantially extend prior theory.

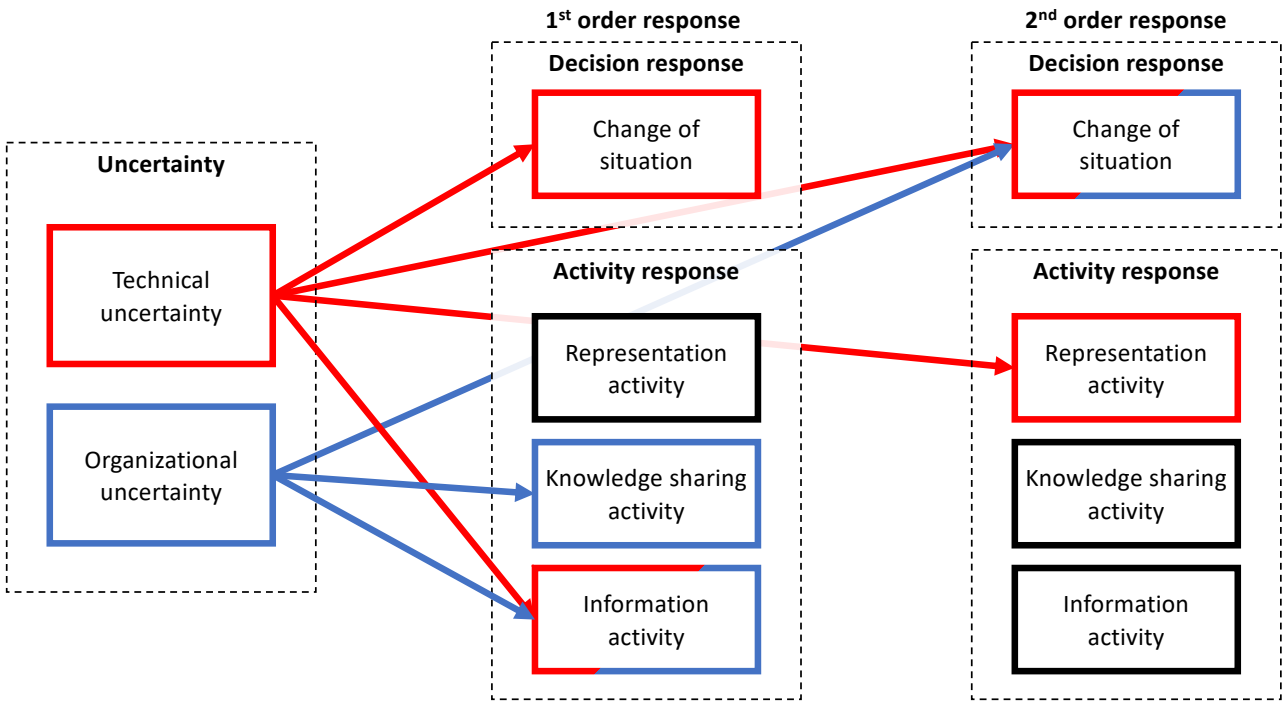

Figure 4 Overview of response patterns for technical and organizational uncertainty

B. Contributions

The above findings offer three major contributions. First, we identify change of situation as a major new type of response to uncertainty in NPD. This is an important development because prior work has focused on activity as the primary response [18], [19], [86], which limits the scope of understanding and guidance on uncertainty resolution. This finding, thus, points to potential new avenues of research as well as new strategies for resolving uncertainty that could not be derived from prior activity focused research. Further, by integrating change of situation (related to goals and context) and activity responses we point to connections with more basic models of human work, such as Activity Theory, where situation and activity are critically related [49], [50]. This contribution paves the way for significant theoretical development not possible via activity only models.

Second, we describe different responses to technical and organisational uncertainty. While prior research has suggested differences in response to uncertainty types [9], [48], these insights are partially contradictory and generally unspecific. However, prior research has also described responses spanning the whole spectrum of activities for almost all uncertainty types, which have typically been studied in isolation [26]–[30]. This contribution resolves prior findings and extends understanding of activity response to different uncertainty types.

Third, we characterize an ordering effect in the responses to uncertainty. We describe distinctly different patterns in the ordering of responses for technical and organizational uncertainty as highlighted above. Again, these are in contrast to prior descriptions that have primarily associated a single type of response to each uncertainty type [26], [27], [30]. Importantly, no prior work (*to the authors' knowledge*) has described any type of ordering effect in response to uncertainty. As such, these insights help to explain and resolve previously contradicting descriptions (e.g. both

information and representation being identified as a response to technical uncertainty [26], [68]). This contribution suggests a more complex relationship between uncertainty and response than previously captured in models that map each uncertainty type to a single main activity, and thus, substantially extends prior work.

C. Limitations

This study has two main limitations. First, the scope of the scenarios used to illustrate each uncertainty type was necessarily limited, as was the range of NPD contexts given. As such, further work is needed to evaluate the robustness of the findings in other NPD contexts, or in the face of radically different uncertainty scenarios. However, the results of this study can still be considered robust as they were consistent across the full range of given scenarios, which themselves were developed from extensive case data as well as iterated with NPD professionals. Further, while the use of scenarios limits the complexity of the situations and responses this is necessary in order to distill the differences and patterns that have resisted description in prior case-based studies, and is typical of experimental design [69], [88].

Second, participants were asked to provide an individual and immediate response to the uncertainty scenarios. As such, further work is needed to understand how this might translate into longer-term responses in a real NPD setting. Further, this individual response might also be affected by the perceptions of the rest of the NPD team. However, individual perception and intention are important predictors of behavior [89], and the core of our results broadly align with expectations from prior research. As such, despite these limitations the reported results provide robust and nuanced insight into the link between uncertainty and activity.

VI. Conclusions

This research set out to better understand the links between technical and organizational uncertainty and project activities in NPD. We presented results from an exploratory quasi-experimental study, utilizing professional and student samples. Our findings produced three major contributions to the NPD management and uncertainty literature. First, we identify "*change of situation*" as a major new type of response to uncertainty in NPD. Second, we describe different specific responses to technical and organisational uncertainty. Third, we characterize an ordering effect in the responses to uncertainty. These contributions substantially elaborate prior theoretical descriptions of the effect of uncertainty type on the relationship between uncertainty and project activity.

In addition to these theoretical contributions, this research has important managerial implications. First, NPD managers are advised to understand the uncertainty type they face and then focus a suitable response in terms of project activity. For technical uncertainty, typical responses include representation activities (e.g. prototyping or simulation) and changes to the situation to enable these (e.g. allocating time or resources for testing, or rescoping project criteria to bypass the uncertainty). For organizational uncertainty, responses include information and knowledge sharing activities (e.g. risk or root cause analyses, team-based planning) to enable the NPD team to progress. Second, these responses to uncertainty can be combined to offer a more substantive approach for reducing uncertainty, compared to typical recommendations for single activity responses. For example, managers facing technical uncertainty could consider varying the constraints of a problem (e.g. performance criteria or delivery timeline) by changes in situation to allow more effective representation activity (e.g. additional user testing). Similarly, for organizational uncertainty knowledge sharing (e.g. team coordination) could be followed by

subsequent changes in situation to adapt the project goals and scope based on the discovered information. Planning for such combinatory responses would enable NPD managers to better tailor their response to the relevant uncertainty type and thus more effectively allocate time and resources when responding to uncertainty.

Finally, this study has important implications for future research. In particular, further work is needed to map and contrast the different response to other uncertainty types more prevalent in other NPD contexts, such as market uncertainty. The research approach described in this paper could facilitate such investigation and would enable elaboration of the insights across uncertainty types. Further, our research points to the need to examine how spontaneous change of situation decisions can be used to reduce and manage uncertainty, and how the various responses are linked to overall project performance. Finally, our identification of change of situation as a major response type suggests the need for reconceptualization of the scope of responses to uncertainty, and further elaboration of activity focused models.

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Appendix

Scenario text

Technical uncertainty: You are in the middle of the NPD project and are testing the cell phone biometric security feature. The feature is crucial since it will substitute the password for unlocking the phone. Individuals in your team know how biometrics work in theory and have had some workshops on it. However, this feature is still not stable and testing is not progressing as expected. The sensors for face detection are not operational as they should be and are easily deceived by makeup and glasses, which in theory should not be problematic. You need to make a decision regarding the next steps you and your team will take to address this challenge.

Technical uncertainty: One of the project tasks is the development of the wireless charging dock. Due to the technical complexity of this dock, the product-development team is working on different product parts in parallel. There is a need for integrating these product parts for the charging dock to be fully functional. The project is stalling because the Mechanics department is still working on the development of the body of the dock. As a result the mock-up is still not ready for testing. You and your team are worried about the integration of the parts. You need to make a decision regarding the next steps you and your team will take to address this challenge.

Organizational uncertainty: You are in the middle of the NPD project, in the phase were the team is working to develop the first product mock-up focusing on the internal parts. You asked Mechanics to be responsible for presenting the final mock-up based on inputs from other departments. They present to you an improved mock up for the phone body, which makes the latest progress from the battery team useless: the new mock-up contains a reduced body size which affects the space available for the battery. You need to make a decision regarding the next steps you and your team will take to address this challenge.

Organizational uncertainty: You have reached the time in the NPD project where the phone body is designed. You are considering variables such as production costs, material type, and possible suppliers. However, Mechanics and User experience disagree between using aluminum and polycarbonate as materials for the phone body. Both options have their advantages but have very different costs and you are on a tight time schedule. You need to make a decision regarding the next steps you and your team will take to address this challenge.