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| Authors | Vandevelde, Anneke;Van Dierdonck, Roland;Clarysse, Bart |
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# THE ROLE OF PHYSICAL PROTOTYPING IN THE PRODUCT DEVELOPMENT PROCESS

A. VANDEVELDE

R. VAN DIERDONCK
e-mail: roland.vandierdonck@vlerick.be

B. CLARYSSE
e-mail: bart.clarysse@vlerick.be

# THE ROLE OF PHYSICAL PROTOTYPING IN THE PRODUCT DEVELOPMENT PROCESS

Anneke Vandevelde, Roland Van Dierdonck and Bart Clarysse

Vlerick Leuven Gent Management School
Associated with the University of Ghent and with the Katholieke Universiteit Leuven
Bellevue 6
B-9050 Gent-Ledeberg
tel: +32 9 210 97 11; fax: +32 9 210 97 00

**Please, send all correspondence to:**

Anneke Vandevelde, Vina Bovypark 40, 9000 Gent, Belgium

And to:

Roland Van Dierdonck, Bellevue 6, 9050 Gent-Ledeberg, Belgium,

roland.vandierdonck@vlerick.be

# THE ROLE OF PHYSICAL PROTOTYPING IN THE PRODUCT DEVELOPMENT PROCESS

## ABSTRACT

The aim of this paper was to achieve a better understanding of the specific role of physical prototyping in the product development process. Data from a survey of 25 companies revealed that the direct effect of prototyping on multidimensional project performance is limited. However, physical prototyping appears to affect process and product concept characteristics. More particularly, it improves interdisciplinary communication, supports a concurrent, time-oriented approach and collaboration in balanced teams. It enhances the project leader's championing, and increases the support of senior management and product quality. Finally, physical prototyping indirectly affects project performance via these modified characteristics.

# INTRODUCTION

Rapid and efficient product development has become an important theme throughout the managerial literature on innovation [11], [41], [70]. The growing attention being paid to prototyping techniques is usually mentioned from this perspective [27], [53], [68]. Even so, the increasing pressure on product complexity and quality is often associated with the endeavour of using and improving prototyping techniques [30], [33], [38]. There seems to be a universal acceptance that prototyping positively affects the product development process and its outcomes.

Empirical studies on the role of prototyping in the product development process are still in their infancy. The innovation management literature on the theme is limited to a few descriptive [46], [73] and empirical studies [31], [72]. So far, the use of CAD systems has received the most attention [21]. Besides this specific literature, there are a few studies, broad in scope, in which prototyping has received attention [14], [61], [80]. The role of prototyping is generally seen in terms of time performance [11], [21]. Thomke [72] compared the impact of computer simulation and rapid prototyping in terms of efficiency, which was defined as the number of eliminated errors divided by the required costs.

Apart from the innovation management literature, a large body of technical literature has been published [27], [30], [44], [45], [53]. This literature ranges from documents of prototyping users [38], and manufacturers [52], [68], to academic literature [76], and it ranges from descriptions of a particular technique [6], [76], to comparisons between techniques [30], [48], [49]. The content, however, seldom goes beyond the technical and commercial aspects. It is interesting though, to see how the literature hints at the complementing role of the different techniques [48], [72], [73].

To better understand the role of prototyping, this study tried to integrate and enrich the insights gained from the innovation management and technical literature. The innovation management literature provides information on the product development process, whereas the technical literature reveals the underlying technical aspects and opportunities of the techniques. Both streams point to the complementing role of the different techniques. The combination of scholarly work with empirical evidence from 53 in-depth repertory grid interviews [77] has led to various hypotheses.

## PROTOTYPING: WHAT IS IN THE WORD?

### A heterogeneous set of techniques

In the wake of Ulrich and Eppinger [73], we define a *"prototype"* as an approximation of the product along one or more aspects of interest. It thus refers to any model that exhibits some aspect of the product that is of interest to the development team. This definition is broad on purpose, and includes prototypes ranging from simple concept sketches to fully functional artefacts. The above authors distinguished two dimensions along which a wide range of prototypes could be classified (see Figure 1).

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*Insert Figure 1 about here*

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The first dimension is the analytical versus physical nature of the prototype. Analytical prototypes represent the product in an intangible, and often mathematical manner. They are based on technologies such as computer-aided design (CAD) [45], [53], [58], computer simulations [46], and quality function deployment (QFD) [1], [29], [36]. Interesting aspects of the product are analysed, rather than physically built. In contrast, physical prototypes are tangible artefacts approximating to the product. Examples of physical prototypes include models that look and feel like the product, proof-of-concept prototypes and experimental models for functional tests [33], [73]. Physical prototyping techniques are based on material deformation, removal or addition processes[1] [50]. This last group has gained tremendous significance since the advent of rapid prototyping techniques in 1987. Kruth [48] has provided an overview and mapped rapid prototyping techniques into two insightful classification schemes.

The second dimension is the degree to which a prototype is comprehensive, as opposed to focused. It reveals the extent to which a prototype implements the various attributes of the product. Comprehensive prototypes implement most, if not all, of the attributes of the product. Note, that the first dimension is mainly based on the technique as such, whereas the classification along the second dimension depends on both the technique and user decisions. For example, even if a technique enabled one to model a car, the user may only prefer to mimic the body of that car.

### The construct of interest

"*Prototyping*" refers to the process of building, testing and analysing prototypes. Building prototypes concerns the creation of a relatively limited number of models in comparison with the final number of manufactured products for commercialization. 'Physical prototyping' or 'the use of physical prototypes' is the central construct in this study. In other words, we have concentrated on

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[1] Examples of processes that deform material to build prototypes are handmade clay models and forging, stamping, extruding, casting and injection moulding techniques ([48], [50]). Material removal processes start with a large quantity of bulk material and remove the excess material. They build prototypes either in a conventional way (e.g., milling and grinding), or in a non-traditional way (e.g., laser and ultrasonic machining). Thirdly, there is the relatively new group of techniques that produce prototypes by usually adding, rather than removing or deforming, material ([4], [68]). A few examples of these rapid prototyping techniques are: stereolithography; solid ground curing; laminated object manufacturing; selective laser sintering: ballistic particle manufacturing; three-dimensional printing; fused deposition modelling; and multiphase jet solidification ([49], [27], [75], [76]). Kruth (1991) classified these into two schemes. The first scheme relates to the way material is created or solidified and depends on the liquid, powder or solid status of the raw material. The second classification refers to the way the shape is built, whether in layers, or directly in a three-dimensional manner.

the use of techniques fitting in the upper half of Figure 1. Since rapid prototyping techniques have gained in significance during the last decade, we attach great interest to this range of techniques.

## DOES PHYSICAL PROTOTYPING AFFECT PROJECT PERFORMANCE?

### The direct effect of physical prototyping on project performance

One may wonder what role physical prototypes fulfil in product development projects. A critical issue is the impact of physical prototyping on project performance, which is considered to be multidimensional [77].

#### *Respect for time*

Fast product development, combined with rapid organizational change and adaptation, can be realized by compression or experiential strategies [21]. The compression model assumes a well-known, rational process and relies on squeezing together the sequential steps of the process. The experiential model assumes an uncertain process and relies on improvization, real-time experience and flexibility. Simultaneously, the experiential model provides enough structure so that people will avoid procrastination and be confident enough to act in uncertain situations. The latter approach is thus more iterative than linear, and more experienced-based than planned. We believe that physical prototyping combines aspects of both strategies.

Physical prototyping is expected to shorten, or eliminate, subsequent steps of the development process, and hence, to compress the process [70]. Although prototyping itself requires some time, we suggest that the global development time reduces. This is deemed particularly true for the rapid prototyping techniques that substantially hasten the building of prototypes [4], [44]. Furthermore, rapid prototyping needs no part-specific tools such as moulds or dies [6], which avoids the long delay times associated with the manufacturing of these tools [50]. Hence, rapid prototyping [30], [60], and more generally, physical prototyping, are expected to hasten the development process. Moreover, prototyping provides designers with near-instant insights into their creations [73], and allows the reduction in, and anticipation of, errors and later problems. As a consequence, any unanticipated rework and any associated problem-solving time, which is hard to estimate, reduce. Hence, we hypothesize that prototyping results in shorter development times as well as an increased adherence to the time schedules.

Besides these compressing aspects, innovation, supported by physical prototypes, can be perceived as iterative problem solving cycles of design-build-test activities [11], or design-build-run-analyse activities [72]. It demonstrates elements of the experiential strategy, which is beneficial to time performance [21]. Just as catalysts and heat accelerate chemical reactions by creating more opportunities for reactions to occur, multiple design iterations accelerate product design by simply offering more opportunities, or chances, for a “hit”. Since experimentation accounts for a significant part of the total innovation time [72], it may mean an important reduction in time. Iterative prototyping further increases speed, because it builds developers’ confidence. Small, frequent failures are very motivating, and promote particularly rapid learning, because they capture people’s attention, but are not yet so large as to raise denial or blocking defences [69]. However, in order to realize time advantages in an experiential mode, it is crucial to create structure and keep focus. We believe that physical prototypes enable this by their milestone-enforcing function. Indeed, Ulrich and Eppinger [73] state that prototypes can serve as milestones to enforce the schedule. Thus, the dangers for speed retards are deemed minimal.

### *Knowledge creation and transfer*

The iterative cycle of design-build-test activities enables building intuition. It is a kind of experimentation, letting the designer efficiently generate “what if?” scenarios [46]. By trying many design variations, developers gain a feeling for the sensitivity of the parameters, and the robustness of the designs. Moreover, the ability to conduct multiple iterations facilitates the evaluation of a single iteration, since comparing alternatives makes strengths and weaknesses more apparent [21]. Furthermore, frequent testing from the early phases on, firmly forces the product development team out of faulty preconceptions [78]. The learning effect is likely to be larger if prototypes are used for functional tests rather than if they are simply used for visualization [5]. Hence, physical prototypes probably result in learning effects.

### ***Respect for budget***

Thomke summarizes that the costs of running an experimentation cycle involve the cost and time of using equipment, material, facilities and engineering resources [72]. Hence, the increased time performance may be translated into a reduction in cost. Moreover, three additional arguments in favour of cost reduction can be formulated due to the advent of rapid prototyping techniques. Rapid prototyping usually requires neither hazardous chemicals nor special utility hook-ups [71], and it is possible to prototype with compact equipment right in the office [4], which avoids extra installation costs. Secondly, rapid prototyping usually needs no expensive workpiece-specific tools such as, moulds or dies [48]. Finally, if masks are used, they are often reusable. For example, the solid ground curing process by Cubital, produces erasable masks by electrostatically charging a graphite toner onto a glass plate as in photocopiers [50]. Other disposable masking techniques apply LCD or LED technology [25]. This helps limit the cost per model. Jacobs [43] estimates the time and cost reduction realized by rapid prototyping to be situated between 40% and 80%. We note that in contrast to the low running costs, the (although reduced [5]) purchase price of rapid prototyping machines is still perceived to be high, which means that many companies go to a service bureau [60]. In addition, the need for skilled employees makes companies look externally.

Besides the lower running costs, the early creation of prototypes enables users to detect and correct flaws before they mushroom into costly and unexpected expenditures [5]. Furthermore, with the advent of rapid tooling as an outgrowth of rapid prototyping [4], tooling decisions can be made later in the process, which saves expensive tooling rework due to either mistakes or design evolution. It eliminates considerable and unexpected costs, and leads to a better adherence to the budget.

In summary, we expect that prototyping leads to learning effects, and an increased regard for budget and time. In summary: *physical prototyping improves project performance (H1).*

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Insert Figure 2 about here

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## The impact of physical prototyping on process and on product concept

Furthermore, we suggest that physical prototyping modifies the way innovation is processed, and helps to improve the product concept. Indirectly, this may result in an improved project performance as well. The model summarizing our hypotheses is represented in Figure 2.

### *Communication*

Prototypes may facilitate communication [27]. They help make some aspects of the design more transparent, and avoid misunderstandings. One reason is that physical prototypes carry their information in an accessible and universal way. “A visual, tactile, three-dimensional representation of a product is much easier to understand than a verbal description, or even a sketch of the product" [73]. Hence, physical prototypes are ideal tools to help reduce asymmetries in information, and make the design more transparent to a wider range of people. Moreover, attention is focused on a specific model, and not on what is vaguely thought about. Hence, prototypes allow for a reduction in ambiguity or for the existence of multiple and conflicting interpretations that refer to Daft and Lengel's [18] notion of equivocality. Discussions are grounded in understandable, concrete facts [21], [43] rather than in abstractions that may lead to endless conflict and interpersonal animosity.

Besides this facilitation of communication effect, physical prototypes enrich communication. They help make tacit knowledge explicit, and can contain extra information by integrating different design aspects. In this manner, they deliver insights into the big picture, and enable the detection of unanticipated phenomena. This is in sharp contrast with analytical tools that never reveal phenomena that are not part of the underlying model on which the prototype has been based [73]. Hence, physical prototypes are information channels carrying information richness, and enable one to cope with uncertainty, defined as the difference between the information an organization has and the information it needs [26]. "There is still no better way to be certain that a complex part contains exactly those features intended for it, than to hold it in your hand, turn it around a few times and look at it from all sides" [42]. In summary, physical prototypes are expected to support communication.

As different functional departments each have their own source of knowledge [19] and have the tendency to create a technical language of their own [54], interdisciplinary communication is often not evident. A tower of Babel syndrome occurs. Physical prototypes probably help reduce this problem. They provide disparate disciplines with a common language for discussion. They enable the transfer of concrete and qualitative information in an accessible and universal way. They keep people focused on the possibilities of the final product, rather than on their own points of view. Hence, interdisciplinary communication is deemed to be supported. In particular, we expect the previous statements to be true for design-manufacturing communication, since apart from conceptual tests at the start of the project, physical prototypes are often used in the downstream stages of the development process to fine-tune or confirm the design [73]. Furthermore, rapid prototyping is developed within the light of computer-integrated manufacturing [50].

We also note that analytical tools are considered as communication tools. Robertson and Allen [63] underlined the role of CAD as a communication technique, rather than as a technique for design and analysis. Hauser and Clausing [37] described QFD as a conceptual map providing the means for interfunctional planning and communication. Therefore, we consider analytical prototyping as a control variable.

*H2: Controlling for analytical prototyping, physical prototyping supports interdisciplinary communication, and in particular, the communication between design and manufacturing.*

### ***Modes of organization***

Physical prototyping allows an efficient management of task dependencies. It enables the integration of various aspects of the product design, which ensures that components and subsystems of the product work together as expected. Comprehensive physical prototypes are probably the most effective integration tools, since they require the assembly and physical interconnection of all parts and subassemblies [73]. This integration, as well as the communication function described previously, is deemed to force coordination between activities, and to enable them to complete development tasks concurrently instead of sequentially [50].

Moreover, prototypes can be used as milestones. They provide tangible goals, demonstrate progress, and serve to enforce the schedule [73]. A high frequency of milestones creates a sense of urgency that keeps people from procrastination [28], and forces them to execute activities simultaneously while keeping them well coordinated. Thus, physical prototypes provide various engineers working on adjoining parts with an actual working model around which to plan their designs [65]. Hence, physical prototypes are considered as tools that encourage simultaneous engineering [12], [50], [66], and enable a parallel and time-oriented organizational mode. In addition, given that analytical prototyping is mentioned in the same breath as simultaneous engineering [23], [66], we found it necessary to consider it as a control variable.

Besides, physical prototyping is expected to support the management of function dependencies. Better interdisciplinary communication and coordination facilitate and encourage co-development in cross-functional teams, which may benefit from the knowledge diversity and the early opportunities for sharing areas of expertise [22]. Physical prototyping may facilitate the information exchange by providing a shared and understandable communication language [2]. Hence, interdisciplinary language barriers [77] reduce, the frequency of communication increases [54], and the potential benefits from cross-functional teams can be exploited to a fuller extent. The design becomes clear even to new members of the team. Hence, the design can benefit from both the expertise of older team members and the open-minded and critical view of new members. Furthermore, a simple physical model keeps a diverse team focused and helps to combine the various perspectives of the different functions in a highly interactive, iterative fashion [19]. Prototyping may be the medium through which various functions agree on a basic design decision.

In summary, physical prototypes are expected to facilitate the co-development in balanced teams, which are defined as teams that include people from different functions and backgrounds, and thus represent a heterogeneous mix of views, skills and knowledge.

*H3a: Controlling for analytical prototyping, physical prototyping supports a parallel, time-oriented approach; H3b: Physical prototyping supports collaboration in balanced teams.*

### *Project leader's championing*

Studies offer numerous descriptions of “championing”, ranging from heroic depictions of a person who “put himself on the line for an idea” [67], to “any individual who makes a decisive contribution to an innovation by actively and enthusiastically promoting its progress through critical stages” [64]. Markham [55] defines champions as people who: a) adopt the project as their own and show personal commitment to it; b) contribute to the project by generating support from other people in the firm; and c) advocate the project beyond job requirement in a distinctive manner. Hence, champions push, persuade, sell and advocate a project [62].

Our study focuses on the project leader, who is the linchpin between senior management and the project team members [8]. A “championing project leader” is defined as a project leader who adopts the project as his or her own and shows personal commitment to it, and who advocates the project beyond his or her project leader tasks in a distinctive manner. A championing project leader is able to recognize, push and demonstrate new ideas and approaches [24], and promotes the project progress.

Physical prototypes focus the attention, demonstrate progress [73], and provide the project leader with a large body of concrete and rich information to understand, follow-up, and evaluate the design and its progress. They help the project leader to recognize ideas, approaches and project progress.

The frequent reassessment of the state of progress means that if actions go off course, then they may be corrected early. Thus, the project leader is stimulated to act and react to problems and changing situations. Moreover, since physical prototypes are easily accessible and understandable, feedback by different people and disciplines is facilitated, and new ideas are captured more easily. In addition, providers of feedback can check quickly whether or not their suggestions have been taken into account: they only need to glance at the next prototype. This may reinforce the project leader's temptation to evaluate feedback and implement it where necessary. In other words, the recognition as well as the push for new ideas and approaches is stimulated.

Note that by visualizing, prototyping [5] makes things more understandable, and hence, facilitates the demonstration of new ideas and approaches. It becomes easier for the project leader to be persuasive and sell his or her project. Hence, prototyping is a tool that helps project leaders to influence others [9]. It is useful to transformational leaders, inspiring others with their vision of an innovation's potential [74], a role that is related to champions [40].

Furthermore, prototyping helps the project leader to fulfil his or her project management tasks. It helps him or her to coordinate and integrate activities; it provides tangible goals and serve to enforce the schedule [73]. Achieving the milestones may provide the project leader with a sense of control and accomplishment that may be motivating [51]. Furthermore, the information included in a tangible prototype helps the project leader to refine and complement his or her thinking, and may further strengthen his or her self-confidence, prestige and motivation. Hence, the project leader may start advocating his or her project in a distinctive manner. He or she starts pushing and demonstrating ideas actively and enthusiastically, which may be promising to the project. He or she adopts the project as his or her own and shows personal commitment to it [55]. In other words, prototyping stimulates him or her into being a championing project leader.

*H4: Physical prototyping stimulates the project leader's championing.*

### ***Senior management's support***

The task of top managers is extremely complex, and includes multiple elements [35]. Managers are responsible for formulating adaptive responses to the environment, as well as for implementing those responses [59]. They are confronted with strategic issues as well as with ongoing, day-in/day-out actions that collectively shape the organization's form [7], [9]. Operating at the organizational apex, senior management confronts information overload and ambiguity [54]. The stimuli are many, and are often vague and competing [34]. Prototyping helps capture the manager's attention despite the many stimuli received during the day. It facilitates and enriches communication, and improves the managers' understanding of the design, which probably strengthens their feeling of being involved and strengthens their support, financially as well as politically. Prototyping thus helps influence top managers. More specifically, proof-of-concept models may stimulate senior managers to attach more attention to the project and allocate the needed resources (budget, time and work forces), whereas comprehensive prototypes in the later stages of the process may keep their attention.

In addition, senior management's support is necessary to gain project go-ahead approval [8]. The concrete character of physical prototypes facilitates the definition and assessment of evaluation criteria, and enables the evaluation of the design and its progress in a quite objective manner.

Hence, at each prototype milestone, the project can be judged along well-defined and clear criteria. Senior management's support may be perceived more clearly and fairly. Moreover, the fact that senior management regularly and explicitly expresses its agreement may be perceived as strong support. Hence, physical prototyping is expected to affect the support of the senior management of the entire product development process. The effect may be part perceptual, part reality.

*H5: Physical prototyping leads to increased attention and support of the senior management.*

### *The product concept*

Physical prototyping helps analysis, verification, testing and optimization of the product concept. Apart from external tests in the market, internal tests on form, fit, function and comfort may be useful to check whether the quality level meets the objectives and expectations. The product quality includes technical aspects as well as more subjective attributes, all of which can be examined by the use of physical prototypes [43]. Technological evolutions have substantially increased the possibilities of modelling [5]. We consider for example, the increasing speed, and the growing number of materials and colour combinations in which rapid prototypes can be built. In addition, improved accuracy levels have widened the range of applications [27]: highly qualitative miniaturization has become possible. Nowadays, there are almost no limitations to the complexity of the created parts [48] (the only problem may be that the prototyping requires particular skills and expertise from the modellers [4], [65]). Hence, quite complex designs that are close to reality, can be modelled quickly and with minimum effort [50]. Pre-assembly and other functional tests are possible [30], [33], [65]. It is clear that technical progress has resulted in more advanced prototyping, which is expected to be beneficial to the final product quality.

The quick learning facilities, the integrating character of prototypes [73], the increased collaboration and cross-functional communication improve the ability to anticipate problems or to identify them early. This helps to improve the product quality, which can be checked at an early stage, and adapted if necessary. Furthermore, physical prototypes improve the ability to find solutions for the detected problems, while still remaining on schedule and within budget. A modification of the data to produce rapid prototypes is not very difficult. Design changes to improve the product quality, which might otherwise have been postponed due to time retards or due to the high cost of new tooling or rework, can be conducted. Moreover, other design options may be explored. This facilitates the evaluation of each option, since comparing designs makes strengths and weaknesses apparent [21]. Furthermore, multiple iterations and tests make designers less likely to become attached to one particular variation, and therefore they adjust the design if changing conditions so warrant. Iteration also improves the cognitive ability to shift with new information [79]. The result is a process in which developers are likely to update and improve their thinking frequently in response to concrete results. It probably results in an overall better product quality. In summary, we expect physical prototyping to improve the product quality [6], [43].

Besides the product quality, we consider the product's innovativeness. In both the literature and our own repertory grid study, there are some arguments in favour of a positive relationship between prototyping and a product's innovativeness, and some against it.

Jacobs postulates that physical prototypes give full rise to the creative spirit of the designers [43]. Rapid prototyping fosters design creativity by enabling the designers to test new and unproven ideas at low cost [46]. Hence, one may argue that prototyping allows for gaining insights into the most radical or crazy ideas, and helps to evaluate, test and optimize them. However, the possibility of reusing old designs and masks, together with the increasing time pressure and the demand for complex products, appears to curb the enthusiasm to create and model radical ideas. Moreover, the negative and devastating implications of design failures [46] may influence designers to apply ideas from a cadre of known, reliable solutions. Another stimulator that makes slight variations preferable is the long preparation time needed to define the data that leads to a new model [21]. Finally, the increased empathy from design to manufacturing due to the improved design-manufacturing communication enabled by physical prototypes, means that the designers tend to better take into account the possibilities, limits and wishes of the manufacturing process at the expense of respect for innovation [77].

Depending on the developers and the company, the net effect of both counteracting forces may probably be either in favour, or against, the newness of the product concept. Considering a heterogeneous set of companies and projects, we hypothesize that there is no relationship between prototyping and the uniqueness of the created product.

*H6a: Physical prototyping improves the product quality.*
*H6b: There is no relationship between physical prototyping and the uniqueness of the created product.*

### The indirect effect of physical prototyping on project performance

As the above discussion has made clear, physical prototyping is expected to modify the process approach and improve the product concept. More particularly, physical prototyping is expected to support the design-manufacturing communication, to change task and function dependencies, to stimulate the project leader's championing and senior management's support, and to improve the product quality. As a final hypothesis, we state that physical prototyping has an indirect effect on the project performance via an improved product quality and the modified process characteristics mentioned above.

Better communication between the design and manufacturing teams is associated with better respect for time requirements [77]. In addition, balanced teams are deemed to have an improved respect for time. This proposition is an extension of the link between cross-functional teams and process performance [12], [14], [81], one of the most robust relationships throughout the literature [8], [21]. Even so, a better championing of the project leader and a concurrent, time-oriented approach contributes to better process performance [12], [50]. Finally, the link between senior management's support, and fast, productive product development is well supported in the literature [8], [15], [81]. Hence, we expect an indirect effect of prototyping on process performance and more particularly, on respect for time.

Furthermore, better design-manufacturing communication corresponds with more prestige [77]. Balanced teams, which can benefit from a diversity of backgrounds and expertise [22], are deemed to have improved knowledge creation and transfer. Furthermore, the shared information, the realized process performance [8], and the better visibility of the team members towards colleagues from other disciplines may affect prestige. Even so, projects that are strongly supported by senior management are probably associated with more prestige since they are deemed important. These projects, moreover, benefit from the so-obtained resources and may give the designers more room to learn, which finally leads to long-term business success.

Since Schon introduced the concept of the product champion in 1963, champions have been thought to have a large positive impact on product development performance [10], [64], [67]. However, rigorous empirical evidence is poor [40]. We note that Markham and Griffin [57] found that using champions as leaders produces a large decrease in cycle time, but does not directly improve the market success of a particular project. Markham [56] found no relationship between champions and profitability, sales volume, product cost, market position, employee benefits, stockholder benefits, and firm image. Championing project leaders probably only enhance the learning effects and the respect for innovativeness, since they recognize and push new ideas and approaches [24]. Finally, a high product quality may result in higher prestige and represent the basis for long-term business success.

In summary, prototypes affect performance indirectly via the considered variables. Mainly, respect for time, prestige, business success, and knowledge creation and transfer, are deemed influential. In other words, we expect an indirect impact on the process and indirect poles of the multidimensional project performance.

*H7: Prototyping indirectly improves project performance via such variables as: a) design-manufacturing communication; b) parallel and time-oriented approach; c) collaboration in balanced teams; d) project leader's championing; e) senior management's support and attention; and f) product quality.*

## METHODOLOGY

In order to test these hypotheses, data were gathered using a detailed questionnaire. It was built on the insights gained in a pre-study based on Kelly's repertory grid method [47]. This method, from cognitive research, was used to detect potential success factors without making assumptions on the construct success in advance. Fifty-three interviewees with different functional backgrounds and interests participated. The sample of companies included those in the design and manufacturing of:

a) adhesives; b) aluminium products; c) measuring equipment; d) electronic components; e) railroad vehicles; f) steel and fibre products; g) suit cases; and h) products for telecommunication and broadcasting.

The key data collection decisions when designing our study were: 1) the selection of product development projects; 2) the generation of dimensions or potential success factors; and 3) the perception of the product development projects in terms of the dimensions. Approximately six relatively recent and self-contained projects were chosen per company. By subsequently comparing different triads of these projects, those similarities and differences were elicited that constituted the dimensions that the interviewee used to differentiate between product development projects. Some initial quantitative data were obtained by rating the presence of, and the importance of, the elicited dimensions per project on an eleven-point scale. Thereby, each respondent rated his or her own generated dimensions for all the projects he or she had compared. Further details on the repertory grid study are described in reference [77].

A purification process eliminated the dimensions that only differed in formulation. Therefore, three researchers independently analysed the interview notes by content analysis, and studied the quantitative data. The remaining list of dimensions was adopted in a questionnaire, which was tested by three colleagues and four people from different companies and business sectors. The questionnaire allowed the collection of more quantitative data, since the repertory grid technique only provided information on the self-supplied dimensions of a respondent.

Each questionnaire represented an evaluation form of a product development project. It contained potential success factors and items concerning project performance. These were measured for their presence and importance to project performance. The scales were similar to those used for the repertory grid study. In addition, information on interdisciplinary interaction, as well as some background information on both respondent and company, were gathered.

The random sample included 25 of the 126 innovative Belgian companies that were contacted. The companies represented a variety of business sectors, including the design and manufacturing of food products, textiles, machinery, chemical and photographic material, micro-electronics, consumer electronics, luggage and handbags, fabricated metal products, electrical machinery and apparatus, television and communication equipment and apparatus, motor vehicles, railway locomotives and rolling stock, cargo handling equipment, lighting materials and components, precision instruments, and plastic products. The sample contained 103 respondents rating 61 different product development projects. Sixty per cent of the projects lasted for a maximum of two years. Ten per cent were categorized as fundamental research. The median respondent had 10 years of work experience, and had been working approximately eight years for the company. Six people reported to him or her. The respondents represented various disciplines: 32% had been working in R&D for the last four years, and 28% in production or quality control. Other functions that were represented in the sample were marketing, purchasing, sales, planning and general management. Fifty-five per cent of the respondents had gained a university degree.

## Measures

All the variables were aggregated measures constructed by principal component analyses. Therefore, all dimensions were qualitatively categorized per theme by three independent researchers. Differences of perception between the researchers were discussed in order to obtain consensus. Employing multiple evaluators increased the reliability of categories. After the elimination of outliers over three iterations, the grouped dimensions were reduced to a stable set of principal components. Dimensions causing instability, low Cronbach alphas ($\alpha$), or eigenvalues below the value of one were not adopted. All principal components were based on dimensions measured for their presence on the eleven-point scale. A "0" indicated that the dimension was completely absent in the project, a "10" indicated that it was strongly present, while the nine intermediate values represented gradation between these values. We now depict the principal components used in this chapter.

***Physical prototyping*** ($\alpha$= 0.70, # dimensions=2) includes: a) the degree to which physical prototypes are used; and b) the degree to which design uses physical prototypes. ***Analytical prototyping*** ($\alpha$= 0.91, # dimensions=4) indicates whether: a) CAD is frequently used during the definition phase; or b) during the design phase; c) whether the development process is characterized by the use of techniques such as QFD, CAD, *etc.* during the definition phase; or d) whether it is characterized by techniques such as FMEA, CAD/CAM, *etc.* during the design phase.

***DM communication*** ($\alpha$= 0.75, # dimensions=4) indicates whether: a) the design receives feedback from production; b) there is a conversation partner for the project in production; c) production obtains adequate information in order to understand the project; and d) there are frequent project meetings.

***Balanced teams*** ($\alpha$= 0.79, # dimensions=4) includes the extent to which the project team: a) includes a balanced mix of functions; b) includes a balanced mix of experience; or c) includes a balanced mix of backgrounds; and d) can be called "cross-functional".

***Championing project leader*** ($\alpha$= 0.87, # dimensions=3) measures the degree to which: a) the project leader adopts the project as his or her own and shows personal commitment to it; b) the project leader quickly reacts on feedback from others; or c) the project leader quickly reacts to changing environments.

***Senior management's support and attention*** (α= 0.70, # dimensions=3) reveals whether: a) the project receives clear support from a senior manager; b) the project is supported by senior management; or c) the project receives a large degree of management attention from the very start of the project.

***Product quality*** (α= 0.75, # dimensions=2) reveals whether the resulting product is characterized by: a) high quality, and b) high reliability. ***Product uniqueness*** (α= 0.65, # dimensions=2) measures whether the created product is: a) unique to the market; and b) has surprising functional characteristics.

***Project performance*** can be represented by a three-polar model, containing process, economic, and indirect poles [77]. The process pole includes such aspects as respect for time, budget, and technical specifications. The economic pole refers to financial and commercial measures. The indirect pole includes the project’s contribution to prestige and business success, respect for innovativeness, and knowledge creation and transfer. Apart from the various success aspects of the multidimensional project performance, we consider a global measure of success by calculating the mean of the seven success aspects mentioned above. This is only one yardstick of global success: the relative weights attached to the seven success aspects may differ over time, respondents and projects.

## Analyses

We checked for second-order relationships in the reported correlation analyses. In the regression models, the underlying assumptions were tested. The data were checked for normality and linearity using the standard regression diagnostics. Multicollinearity was checked for using point correlations between the different independent variables. All analyses were exploratory in nature. The unit of analysis was the respondent[2]. We only considered the respondents' rating of a project in which

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[2] We checked for interdependency between respondents. We successively conducted a paired-sample correlation-test for each of the variables considered. The groups compared by the test were composed as follows. We took into account the data from the projects

physical prototyping was deemed important (rating on the importance scale > 5.5/10). Eleven respondents were excluded. The remaining sample contained 23 companies, which represented the business activities mentioned previously.

## RESULTS

The results were organized into four areas. They concern: 1) the direct effect of physical prototyping on project performance; 2) the impact of physical prototyping on process and product concept; and 3) the indirect effect of physical prototyping on project performance.

### The direct effect of physical prototyping on project performance

Our first hypothesis suggested a direct effect of physical prototyping on project performance. However, regression analyses (Table 1) revealed no significant impact either on the global success (model 1), or on any of the success aspects considered separately (models 1a through 1g). We therefore controlled for the use of analytical prototyping, and for the described process and product concept characteristics.

A few additional correlation analyses between physical prototyping and the 23 dimensions that compose the seven success aspects show (only) two significant relationships. The first concerns the link between prototyping and process efficiency (ρ=0.330**, sign=0.005, N=72). The second stresses the relationship between prototyping and knowledge creation (ρ=0.287*, sign=0.015, N=71), although the link is not as strong as we expected. In other words, prototyping slightly correlates with knowledge creation, but not with knowledge transfer. In addition, prototyping is associated with process efficiency. In contrast, no relationship was detected between prototyping

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that were evaluated by more than one respondent. Afterwards, we equally divided all the data on the same project into two groups. This was carried out for all the projects of the sample. In projects that were evaluated an odd number of times, the data from one respondent were eliminated. The paired-sample correlation coefficients revealed that there was no relationship between the groups.

and the degree to which the initial planning is met, or the degree to which the new product reaches the market on time. Hence, no effect was found on respect for time (model 1a).

Insert Table 1 about here

A first interpretation of the results is that physical prototyping has no direct effect on project performance, or that the design of our research has failed to reveal the relationship. For example, it may be that only a few physical prototyping techniques affect performance, and thus, that the construct of physical prototyping is too broad.

Furthermore, the assumption that prototyping is actually used in an experiential strategy may be false. Only when prototyping can be achieved sufficiently quickly, cheaply and easily enough does iterative testing become possible, and people start considering an experiential strategy. From this perspective, the technological evolutions towards rapid prototyping and more particularly, desktop and instant manufacturing, are probably fruitful [48]. We note that if prototyping only brings insights by integrating components and subassemblies, and not by experiential learning, prototyping may hasten the learning process, but creates little extra knowledge.

Even so, perhaps quite a few companies had outsourced prototyping, which would hinder the experiential mode in the outsourcing company. When for example, the creation of rapid prototypes is outsourced [60], the outsourcing company only tests and analyses the prototypes created by another company, which reduces the fast, iterative testing and the experiential learning effects in the outsourcing company.

Besides, even if physical prototyping allows for work in an experiential mode, time advantages are only realized if one creates structure and keeps focus. It may be that the visual character of physical prototypes, which may help focus attention and give structure, or the use of prototypes as milestones that enforce the schedule, are not exploited well today. Milestones create a sense of order and routine that can serve as a counterpoint to the more freewheeling and even chaotic activities of iteration and testing [79]. Hence, the actual use and management of prototypes are both important.

Even so, if the learning function of prototypes [73] is not well used, there is still unexpected rework and problem solving, which impede a better respect for time and budget. Besides this, it is crucial to take care that various people get the chance to learn, and that there is room to realize knowledge transfer.

Additionally, misguided efforts may cause a waste of time [30], [73]. Hence, even if prototyping is conducted efficiently, an ineffective management may eliminate the potential time or budget benefits. Indeed, one can decide to conduct not well thought-out experiments. Cost and benefit analysis should be kept in mind when thinking of additional prototyping tests. Another example of misguided efforts is the building and debugging of prototypes that do not really contribute to the goals of the overall development project. This is called the hardware swamp [13]. Hence, the choices made by the experimenter are crucial [72]. Unnecessary procrastination and misguided efforts should be avoided [21]. From the previous statements, it becomes clear that the lack of a relationship between prototyping and project performance may be related to the actual use and management of prototypes.

A final explanation may be related to the fact that expectations have been raised. As we found, prototyping correlates positively with process efficiency. For example, the organization may take into account this increased efficiency in its planning and attribution of resources. Hence, either the project is planned in a shorter time period, or fewer resources are attributed to the project. Hence, no relationship is found between prototyping and respect for time. Or, it may be that the increased efficiency due to prototyping goes hand in hand with an increasingly demanding environment, which asks for shorter development times, and explains why no relationship is found with the degree to which the product reached the market on time.

In summary, the direct impact of physical prototyping on project performance is found to be limited. We made various propositions on how to interpret the results. Further research on the use and role of prototyping is deemed to be useful.

## The impact of prototyping on process and on product concept

The second, third, fourth, fifth and sixth hypotheses consider the impact of physical prototyping on both development process and product concept. Various regression analyses were conducted to test these hypotheses.

### ***Communication***

Table 2 confirms the second hypothesis: physical prototyping supports interdisciplinary communication between design and manufacturing (model 2a). Hence, it helps to make a project more transparent, which is supported by correlation analysis between physical prototyping and the transparency of the task ($\rho=0.306^{**}$, sign=0.025, N=54). Better communication is further associated with an increased empathy from design to manufacturing, and smooths the production start-up [77]. Hence, we can state that prototyping fulfils a role at the design-manufacturing interface. This is also illustrated by the positive relationship between prototyping and the degree of completion of the design at its introduction in production (ρ=0.341**, sign=0.004, N=71). In summary, prototyping affects not only design-manufacturing communication, but the whole interface.

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Insert Table 2 about here

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Besides its impact on design-manufacturing communication, physical prototyping appears to improve the communication with engineering (model 2b). However, no relationship was found between physical prototyping and the design-marketing interface (model 2c). Here again, we may wonder if the tools are not supportive, or if the way prototyping was used and managed, explains the lack of a relationship.

For example, one choice in managing prototypes is the selection of the people involved in the prototyping process. The repertory grid study taught that design is heavily involved in prototyping today. Similar conclusions are derived from paired sample t-tests between the presence and the perceived importance mean (Table 3). Design was found to be involved rather too heavily (pair 1), whereas marketing (pair 2) and manufacturing (pair 3) were far less involved than is perceived as beneficial to project performance. Hence, a more interdisciplinary approach is suggested.

We now explore the added value of an interdisciplinary approach in more depth (Table 4). Regression analyses reveal that the involvement of manufacturing is beneficial to the design-manufacturing communication (model 2h), but negatively affects design-marketing communication. The involvement of marketing improves the communication with marketing (model 2i). Involving manufacturing or marketing does not influence the communication between design and engineering, which is a rather reasonable conclusion. Looking at design-marketing communication, we see that not prototyping as such (model 2c), but the fact that prototyping enables the involvement of marketing (Table 4), is beneficial to interdisciplinary communication. We conclude that not only physical prototyping but also the way prototyping is managed, determine the effect on interdisciplinary communication.

Insert Table 3 about here

Insert Table 4 about here

So far, we have described the effect of prototyping on internal communication. Inspired by Ulrich and Eppinger [73], we wondered whether prototyping also had an impact on the external communication with customers and business partners (*e.g.*, suppliers, co-development partners). At first sight, there were no links at all (Table 2: models 2d and 2f). However, repeating the analyses for the sub-samples containing the projects where, respectively, the customer (model 2e) and supplier involvement (model 2g) were deemed important (ratings on the importance scale >5.5/10), reveals the following. Prototyping indeed improves the communication with the customer (Model 2e). This is an interesting finding since the importance of prototyping together with the customer has been underlined several times in the literature [3], [61]. Cooper [16] found that if prototyping is used, it makes up about 72% of the entire product development process, including 27% for prototype trials with customers. Model 2g reveals that physical prototyping influences slightly the communication with business partners ($p<0.1$). Further research is suggested to examine whether prototyping really has a limited effect, or whether it is helpful but not used to its full extent today.

Although analytical tools were not the focus of this study, we note some interesting findings. Analytical prototypes seem to stimulate (only) the communication between design and engineering (model 2b) and the communication with the co-development business partner (model 2g). One may wonder whether the construct of 'analytical tools' is not too heterogeneous: depending on the specific technique such as QFD or CAD, the effects may differ. If not, we may conclude that analytical tools have a limited effect on interdisciplinary communication. This may be due to the fact that the technical CAD language requires some skill of the prototyping analyst. If, thereby, the information included in a prototype is badly or not perceived, the communication function of prototypes diminishes or even disappears. Therefore, CAD techniques are expected to be more appropriate in stimulating communication between people having a similar technical-oriented language, such as design and engineering for example, or design and external co-developers. Hence, CAD appears to be a donor of an electronic communication net, which can expedite communication among designers and technically skilled people. Our results also confirm that QFD does not sufficiently link design to marketing [66]. We conclude that the interdisciplinary communication function of physical prototypes is found to be stronger than that of analytical prototypes. We found evidence for Jacobs' statement ([43], p20): "the less abstract the information is, the easier information is exchanged between people having different functions, background or interest".

### ***Organizational modes***

Table 5 reveals a link between physical prototyping and a concurrent, time-oriented process approach (model 3a). In other words, physical prototyping allows an efficient handling of task dependencies: it enables one to conduct some development tasks concurrently, which would be normally completed sequentially. Model 3b further stresses that physical prototyping supports an adequate management of function dependencies. It is associated with collaboration in balanced teams, in which people with a different function, experience or background work together. Hence, the third hypothesis concerning the effect of prototypes on the organizational mode is supported.

Insert Table 5 about here

Insert Table 6 about here

### *Project leader and senior management*

The fourth and fifth hypotheses are supported. Model 4 (Table 5) reveals that physical prototyping stimulates the project leader's championing. Physical prototypes stimulate the project leader to show personal commitment to the project and advocate the project beyond his or her project leader tasks in a distinctive manner. They help him or her in recognizing and pushing ideas and approaches, and in promoting a project's progress. Furthermore, physical prototypes stimulate the support and attention of senior management (Table 6: model 5). Note that physical prototyping, used as a milestone-enforcing tool, requires that senior management regularly and explicitly expresses its support. Hence, the stronger support may be partly perception.

### *Product concept*

In line with the technical literature [6], [43], physical prototypes are found to be enablers of a superior product quality (Table 6: model 6a). Furthermore, we found no contradiction with our hypothesis that there is no relationship between physical prototyping and the newness of the product concept (model 6b). Hence, our results are in line with the sixth hypothesis.

## Indirect effect of physical prototyping on project performance

The previous paragraphs discussed that physical prototyping affects the process approach and product concept. Physical prototyping was found to support interdisciplinary communication, to help manage task and function dependencies, to strengthen the project leader's championing, to stimulate senior management's support, and to improve the product quality. We now examine whether physical prototyping affects project performance indirectly via its impact on process characteristics and product quality.

Insert Table 7 about here

Two-step regression analyses were conducted between prototyping and project performance (Table 7). The process and product concept characteristics were the instrumental variables. The results demonstrate that physical prototyping indeed indirectly affects project performance (model 7), which confirms the seventh hypothesis. In particular, prototyping improves respect for time (model 7a), business success (model 7g), and to a lesser extent, knowledge creation and transfer (model 7c). In summary, physical prototyping affects project performance indirectly, rather than directly.

## CONCLUSION

Companies are under increasing pressure to develop complex products efficiently and effectively [11], [17], [41], [70]. In order to meet this challenge, a myriad of methods and techniques has been developed. The genesis and evolution of prototyping techniques were also depicted in the light of this demanding environment [38], [53], [68]. Since the advent of rapid prototyping in 1987, physical prototyping techniques came to the forefront as promising tools [48]. The recent evolution in physical prototyping techniques and the actual lack of attention to this theme in the management literature inspired us to examine the role of physical prototyping in more depth.

### *Role of prototyping*

A major role of prototyping is its function as a communication tool [73]. Physical prototypes seem to be an important tool for interface management. In this research, prototyping was found to support the communication between design and manufacturing, and between design and engineering.

Furthermore, it seems a useful tool to communicate with customers. In contrast, the study found only a slight effect of prototyping on the communication with business partners. Furthermore, there seems to be no impact on the design-marketing interface, unless marketing is strongly involved during the prototyping process. This probably illustrates that not only prototyping in itself, but also the way prototypes are used and managed, are important. We note that, despite the importance of involving various functions in the prototyping process, our study revealed that the designers are the core actors on the prototyping scene today. Marketing and manufacturing are involved far less than is perceived to be beneficial to project performance.

Additionally, our study hints at the different roles physical and analytical prototyping fulfil. We observed that, in contrast to physical prototypes, which support interdisciplinary communication, analytical tools mainly support communication between technically skilled people. Hence, the study subscribed to both the managerial [72], [73] and technical literature [48], which stress the complementing role of different techniques. We note that a few techniques try to combine the benefits of physical and analytical prototyping. Virtual reality, for example [20], [45], which of itself is not physical, tries to mimic tangible techniques: a haptic interface allows transmitting forces back to hand and fingers in a way that resembles the sensation of touching real objects.

Besides the communication function, physical prototyping seems to support an adequate management of task and function dependencies. More particularly, it supports a concurrent, time-oriented approach, and the collaboration in teams composed of people from different functions and backgrounds. Furthermore, it stimulates the project leader's championing and senior management's support and attention. In line with the technical literature [6], [43], physical prototyping enables a superior product quality. In summary, physical prototypes affect the process approach and product quality. Hereby, the development process is affected from the very start of the project to the downstream stages. As we suggested, we found no evidence for a relationship between prototyping and the innovativeness of the product concept.

The study also revealed that prototyping improves project performance. The effect seems to be indirect rather than direct. More particularly, prototyping indirectly improves respect for time, contribution to business success and to a lesser extent, to knowledge creation and transfer. No relationship, either direct or indirect, was found between physical prototyping and economic success, prestige, respect for innovativeness, and budget and technical specifications.

### ***Future research***

Given the explanatory nature of this study, further research is useful. Various propositions were put forward to explain the limited direct effect of prototyping on project performance. For example, one may investigate whether the limited effect is due to the actual use and management of prototypes. Is rapid prototyping used in sub-optimized ways today [65]? It would be interesting to further explore whether prototyping can be better used and managed, and hence, enlarge its role. Can it be more supportive to the communication with suppliers and to the design-marketing communication for example?

Other interesting areas of future research are the progress prototyping is making and its impact on development process and project performance. Furthermore, one may further explore the potential differences between the role of analytical and physical techniques. In order to refine our study, we advise that the wide range of physical and analytical prototyping techniques be split. This can be done by considering the different techniques separately, or by selecting more and other classification characteristics than the analytical versus physical character. It may also be useful to investigate the role of prototypes during the product development process longitudinally. Physical prototypes used as proof-of-concept models probably have a role other than as prototypes used later in the process. Finally, we note that it would be interesting to conduct large-scale analyses and to replicate our study in a variety of settings.

# REFERENCES

[1] Y. Akao, *Quality Function Deployment, Integrating customer requirements into product design.* Productivity Press, Cambridge, MA, 1990.

[2] T.J. Allen and S. Cohen, “Information flows in R&D labs”, *Administrative Science Quarterly*, vol. 14, pp. 12-19, 1966.

[3] A. Balbontin, B. Yazdani, R. Cooper and W.E. Souder, “New product development success determinants in American and British firms”, *International Journal of Technology Management*, vol. 17, no.3, pp. 259-280, 1999

[4] P.H.W. Balsmeier and W.J. Woisin, “Rapid prototyping: state-of-the-art manufacturing”, *Industrial Management,* 1997.

[5] B.A. Beckert, “Refining rapid prototyping systems”, *Computer - Aided Engineering,* 1999.

[6] D.L. Bourell, R.H. Crawford, H.L. Marcus, J.J. Beaman and J.W. Barlow, “Selective Laser Sintering of Metals”, *Manufacturing Science and Engineering*, vol. 68, no.2, ASME, pp.519-528, 1994.

[7] J.L. Bower, *Managing the resource allocation process*, Boston MA: Harvard University Press, 1970.

[8] S.L. Brown and K.M. Eisenhardt, “Product development: past research, present findings and future directions”, *Academy of Management Review*, vol. 20, no.2, pp. 343-378, 1995.

[9] R.A. Burgelman, “A process model of internal corporate venturing in the diversified major firm”, *Administrative Science Quarterly*; vol. 28, pp. 223-244, 1983.

[10] A. Chakrabarti, “The role of champion in product innovation”, *California Management Review*, vol. 17, no.2, pp. 58-62, 1974.

[11] K. Clark and T. Fujimoto, “Lead time in automobile product development - explaining the Japanese advantage”, *Journal of Engineering Technology Management*, vol. 6, no.1, pp. 25-58, 1989.

[12] K. Clark and T. Fujimoto, *Product development performance*. Boston: Harvard Business School Press, 1991.

[13] D. Clausing, *Total quality development*. ASME Press, New York, 1994.

[14] R.G. Cooper and E.J. Kleinschmidt, “Major new products: what distinguishes the winners in the chemical industry”, *Journal of Product Innovation Management,* vol. 2, pp. 90-111, 1993.

[15] R.G. Cooper and Kleinschmidt, “New products: what separates winners from losers?”, *Journal of Product Innovation Management*, vol. 4, pp. 169 - 184, 1987.

[16] R.G. Cooper, “The new product process: an empirically-based classification scheme”, *R&D Management,* vol. 13, no.1, pp. 1- 13, 1983.

[17] R. Cordero, “ Managing speed to avoid product obsolescence “, *Journal of Product Innovation Management*, vol. 8, pp.283-294, 1991.

[18] R.L. Daft and R.H. Lengel, “Organisational information requirements, media richness and structural design”, *Management Science*, vol. 32, pp. 554-571, 1986.

[19] D. Dougherty, “Interpretative barriers to successful product innovation in large firms”, *Organisation Science,* vol. 3, pp. 179-202, 1992.

[20] R.A. Earnshaw, J.A. Vince and H. Jones, *Virtual Reality Applications*, Academic Press, 1995.

[21] K.M. Eisenhardt and B.N. Tabrizi, “Accelerating adaptive processes: product innovation in the global computer industry”, *Administrative Science Quarterly*, vol. 40, pp. 84-110, 1995.

[22] D. Eppinger Steven, H. Fine Charles and K. Ulrich, “Interdisciplinary product design education”, *IEEE Transactions on Engineering Management,* New York, vol. 34, no. 4, pp. 301-305, 1990.

[23] B. Evans, “Simultaneous Engineering”, *Mechanical Engineering,* vol. 110, no. 2, pp. 38-39, 1988.

[24] A.L. Frohman, “The performance of innovation: managerial roles”, *California Management Review*, vol. 20, no.3, pp. 5-12, 1987.

[25] E.V. Fudim, “Three-dimensional prototyping by simultaneous contact imaging of whole slices”, *National Computer Graphics Association Conf.*, Chicago, April, 1991.

[26] J.R. Galbraith, *Designing complex organisations*. Reading, Ma: Addison-Wesley, 1973.

[27] M. Geiger, “Advances in materials technology monitor, UNIDO, vol. 1, no. 1, 1995.

[28] C.J.G. Gersick, “Time and transition in work teams: toward a new model of group development”, *Academy of Management Journal,* vol. 31, no.1, pp. 9-31, 1988.

[29] C.P.M. Govers, “What and how about quality function deployment”, *International Journal Production Economics*, vol. 46-47, pp. 575-585, 1996.

[30] M. Greul, E. Pintat and M. Greulich, “Rapid prototyping of functional metallic parts”, *Computers in Industry*, no.28, pp. 23-28, 1995.

[31] A. Griffin and J.R. Hauser, “Patterns of communication among marketing engineering and manufacturing - a comparison between two new product teams”, *Management Science*, vol. 38, no.3, 360-373, 1992.

[32] A. Griffin and J.R. Hauser, ‘Integrating R&D and Marketing: a review and analysis of the literature’, *Journal of Product Innovation Management,* vol. 13, pp. 191-205, 1996

[33] H. Haferkamp, F.W. Bach, F. von Alvensleben and J. Gerken, “Laser Prototyping: metal models in minutes”, *Photonics Spectra*, May, pp.122-124, 1996.

[34] D.C. Hambrick and P.A. Mason, “The organisation as a reflection of its top managers”, *Academy of Management Review*, vol. 9, pp. 195-206, 1984.

[35] D.C. Hambrick, “Top management Groups: a conceptual integration and reconsideration of the team label”, Research in Organisational Behaviour. Vol. 16, pp.171-213, 1994.

[36] J. Hauschildt, “Towards measuring the success of innovations”, *IEEE Transactions on Engineering Management*, vol. 7, pp. 605-609, 1991.

[37] J.R. Hauser and D. Clausing, “The house of quality”, *Harvard Business Review*, 66 (May-June 1988), pp. 63-73, 1988.

[38] J. Hayes, *Rapid prototyping allows fast design changes*. Research & Development, Barrington, 1998.

[39] R.H. Hayes, S.C. Wheelwright and K. Clark, *Dynamic manufacturing,* New York: Free Press, 1988.

[40] J.M. Howell and C.A. Higgins, “Champions of technological innovation”, *Administrative Science Quarterly*, vol. 35, pp. 317-341, 1990.

[41] M. Iansiti, “Shooting the rapids, managing product development in turbulent environments”, *California Management Review*, vol. 38, no.1, pp. 37-58, 1995.

[42] P. Jacobs, *Rapid prototyping and manufacturing, fundamentals of stereolithograph.* SME, Dearborn, 1992.

[43] P. Jacobs, *Stereolithography and other RP&M Technologie.* From rapid prototyping to rapid tooling, ASME Press: New York, 1996.

[44] R. Jamieson and J. Hammond, *Rapid Wind Tunnel Prototype Using Stereolithography and equivalent technologies.* Proc. ICAS, pp.1712-1722, 1995.

[45] S. Jayaram, *Virtual Reality and CAD/CAM, the CAD/CAM Handbook.* Carl Machover, pp. 409-437, 1995.

[46] T.A. Kappel and A.H. Rubenstein, “Creativity in design: the contribution of information technology”, *IEEE Transactions on Engineering Management,* vol. 46, no2, 1999.

[47] G.A. Kelly, *The Psychology of Personal Constructs.* Norton, New York, 1955.

[48] J.P. Kruth, “Material incress manufacturing by rapid prototyping techniques”, *Annals of the CIRP,* Stanford, Paolo Alto, USA, vol. 40, no.2, pp.603-614, 1991.

[49] J.P. Kruth, *Direct production of metallic parts by rapid prototyping,* Proc. of 12th international congress ‘laser 95': key technology laser: challenge for the factory 2000, München, pp123-134, 1995.

[50] J.P. Kruth, “Manufacturing techniques for rapid prototyping and concurrent engineering”, G. Halevi and R.D. Weill, *Elsevier Science Publishers B.V.* (North-Holland), IFIP, pp.51-83, 1992.

[51] E. Langer, “The illusion of control”, *Journal of Personality and Social Psychology*, vol. 32, pp. 311-328, 1975.

[52] H.J. Langer, J. Reichle and M. Shellabear, *Rapid Prototyping with the Layer Manufacturing Techniques Laser Stereolithography and Laser Sintering*. Proc. of 12th international congress ‘laser 95': key technology laser: challenge for the factory 2000, München, pp.115-122, 1995.

[53] C. Machover, *The CAD/CAM Handbook*. McGraw-Hill, 1995.

[54] J.G. March and H. Simon, *Organisation.* New York: John Wiley, 1958.

[55] S.K. Markham, “A longitudinal examination of how champions influence others to support their projects”, *Journal of Product Innovation Management*, vol. 15, pp. 490-504, 1998.

[56] S.K. Markham, “Corporate championing and antagonism as forms of political behaviour: an R&D perspective”, *Organisation Science,* vol. 11, no.4, pp. 429-447, 2000.

[57] S.K. Markham and A. Griffin, “The breakfast of champions: associations between champions and product development environments, practices and performance”, *Journal of Product Innovation Management*, vol. 15, pp. 436-454, 1998.

[58] C. McMahon and J. Browne, *CAD/CAM, from principles to practise.* Wockingham, Addison Wesley, 1995.

[59] R.E. Miles and C.C. Snow, *Organisational strategy, structure and process.* New York: McGraw-Hill, 1978.

[60] R. Mills, “Put RP into design”, *Computer-Aided Engineering,* 1999.

[61] M.E. Parry and X.M. Song, “Identifying new product success in China”, *Journal of Product Innovation Management*, , vol. 11, pp.15-30, 1994.

[62] E.B. Roberts and A.C. Fusfuld, Critical function: needed roles in the innovation process; in: Career Issues in Human Resource Management, R. Katz (ed.) Englewood Cliffs, NJ: Prentice Hall, pp. 182-207, 1981.

[63] D.C. Robertson and T.J. Allen, “Cad system use and engineering performance”, *IEEE Transactions on Engineering Management*, vol. 40, no.3, pp. 274-282, 1993.

[64] R. Rothwell, C. Freeman, A. Horsley, V.T.P. Jervis, A. Robertson and J. Townsend, “SAPPHO updated - Project Sappho phase II”, *Research Policy*, vol. 3, pp. 258-291.

[65] D.A. Schaub, K.R. Chu and D.C. Montgomery, “Optimising stereolithography throughput”, *Journal of Manufacturing Systems*, 1997.

[66] R. Schmidt, “The implementation of simultaneous engineering in the stage of product concept development: a process orientated improvement of quality function deployment”, *European Journal of Operational Research*, 1997.

[67] D.A. Schön, “Champions for radical new inventions”, *Harvard Business Review*, vol. 41, pp. 77-86, 1963.

[68] M. Shellabear, J. Reichle and H.J. Langer, *Rapid Prototyping with the Layer Manufacturing Techniques Stereolithography and Laser Sintering, paper for ISEM-XI*, Lausanne, April 17th-20th, 1995.

[69] S.B. Sitkin, “Learning through failure: the strategy of small losses”, *In B.M. Staw and L.L. Cummings (eds.); Research in Organisational Behavior*, Greenwich CT: JAI Press, vol. 14, pp. 231-266, 1992.

[70] G. Stalk and T.M. Hout, *Competing against time: how time-based competition is reshaping global market.* The Free Press, New York, 1990.

[71] T. Stevens, “Fashion models: compact and inexpensive, new office-friendly rapid prototyping devices promise faster time to market, higher quality new products, and more”, *Industry Week*, vol. 245, no.18, pp. 51-53, 1996.

[72] S.H. Thomke, “Managing experimentation in the design of new products”, *Management Science,* vol. 44, no.6, pp. 743-762, 1999.

[73] K.T. Ulrich and S.D. Eppinger, *Product Design and Development.* McGraw-Hill, Singapore, 1995.

[74] A. Van de Ven; “Central problem in the management of innovation”, *Management Science*, vol. 32, pp. 590-607, 1986.

[75] B. Van der Schueren and J.P. Kruth, Laser Based Selective Metal Powder Sintering, a feasibility study, proceedings 26th int. CIRP Seminar on Mfg Systems, Proc. laser assisted net shape enginering conf. (LANE, 1994), Erlangen, vol.2, pp. 793-802, 1994.

[76] B. Van der Schueren and J.P. Kruth, “Powder Deposition in Selective Metal Powder Sintering”, *Rapid Prototyping Journal*, vol.1, no.3, pp. 197-211, 1995.

[77] A. Vandevelde, *The design–manufacturing interface and the role of prototyping with respect to the performance of a new product development project*, Unpublished dissertation, February, University of Ghent, 2001.

[78] E. Von Hippel and M. Tyre, *How learning by doing is done: problem identification in novel process equipment.* Working paper, Sloan School MIT, 1993.

[79] K.E. Weick, “The collapse of sense making in organisations: the Mann Gulch disaster”, *Administrative Science Quarterly*, vol. 38, pp. 628 - 652, 1993.

[80] S.C. Wheelwright and K.B. Clark, *Revolutionising product development: quantum leaps in speed, efficiency and quality.* New York: Free Press, 1992.

[81] B.J. Zirger and M. Maidique,” A model of new product development: An empirical test”, *Management Science*, vol. 36, pp. 867-883, 1990.

## TABLE 1

## Regression analyses examining the impact of physical prototyping (PP) on project performance.

| | **Model 1: aggregated success** | | **Model 1a: respect for time** | | **Model 1b: respect for budget & technical specs** | | **Model 1c: knowledge creation & transfer** | |
|---|---|---|---|---|---|---|---|---|
| | beta | s.e. | beta | s.e. | beta | s.e. | beta | s.e. |
| Intercept | ** | 0.364 | ** | 1.651 | ** | 1.556 | * | 1.461 |
| Prototyping | -0.265 | 0.225 | 0.037 | 0.330 | -0.264 | 0.265 | -0.033 | 0.507 |
| Adj.$R^2$ | 0.08 | | 0.17 | | 0.06 | | 0.00 | |
| p | 0.326 | N: 26 | 0.113 | N: 35 | 0.345 | N: 30 | 0.511 | N: 38 |

| | **Model 1d: contribution to prestige** | | **Model 1e: respect for innovativeness** | | **Model 1f: contribution to business success** | | **Model 1g: financial, commercial success** | |
|---|---|---|---|---|---|---|---|---|
| | beta | s.e. | beta | s.e. | beta | s.e. | beta | s.e. |
| Intercept | ** | 2.311 | ** | 1.456 | ** | 1.778 | ** | 1.746 |
| Prototyping | -0.009 | 0.475 | -0.051 | 0.165 | -0.045 | 0.368 | -0.041 | 0.296 |
| Adj.$R^2$ | 0.00 | | 0.00 | 0.257 | 0.25* | | 0.00 | |
| p | 0.754 | N: 36 | 0.945 | N: 36 | 0.037 | N: 37 | 0.804 | N: 35 |

*Legend: * = significance level < 0.05; ** = significance level < 0.01; no interaction effects were detected; s.e.: standard error.*

*We controlled for: 1) design-manufacturing communication; 2) parallel and time-oriented approach; 3) collaboration in balanced teams; 4) championing of the project leader; 5) support and attention of senior management; 6) product quality; and g) analytical prototyping.*

# TABLE 2
# The impact of physical prototyping (PP) on communication.

| **Regression analyses** | **Internal, interdisciplinary communication** | | | | | |
|---|---|---|---|---|---|---|
| | **Model 2a: communication design & manufacturing** | | **Model 2b: communication design & engineering** | | **Model 2c: communication design & marketing** | |
| | beta | s.e. | beta | s.e. | beta | s.e. |
| Intercept | | 0.121 | ** | 0.295 | ** | 0.325 |
| Control | 0.151 | 0.125 | 0.224* | 0.297 | 0.003 | 0.327 |
| PP | 0.491** | 0.119 | 0.335** | 0.297 | 0.211 | 0.327 |
| Adj.$R^2$ | **0.24**** | | **0.14*** | | 0.02 | |
| p | 0.00 | N: 55 | 0.049 | N: 55 | 0.207 | N: 55 |

| **Regression analyses** | **External communication** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Model 2d: communication with customer** | | **Model 2e: communication with customer (')** | | **Model 2f: communication with business partners** | | **Model 2g: communication with business partners ('')** | |
| | beta | s.e. | beta | s.e. | beta | s.e. | beta | s.e. |
| Intercept | | 0.143 | ** | 079 | | 0.143 | ** | 0.099 |
| Control | 0.164 | 0.149 | .104 | 0.84 | 0.208 | 0.148 | 0.346* | 0.101 |
| PP | -0.009 | 0.141 | .311* | 0.85 | -0.022 | 0.141 | 0.249 | 0.091 |
| Adj.$R^2$ | 0.00 | | **0.08*** | | 0.00 | | **0.13*** | |
| p | 0.493 | N: 55 | 0.050 | N: 49 | 0.317 | N: 55 | 0.026 | N: 40 |

*Legend: * = significance level p < 0.05; ** = significance level p < 0.01; s.e. = standard error. We controlled for differences in analytical prototyping.*

*(') = only projects in which communication with the customer is important are included in the sample.*

*('') = only projects in which communication with business partners is important are included in the sample.*

# TABLE 3
## Paired sample t-tests between the presence and perceived importance of prototyping items.

| | | Paired Differences | | | t | Sig. (2-tailed) |
|---|---|---|---|---|---|---|
| | | Mean | Std. Deviation | Std. Error | | |
| Pair 1 | involvement of designers | .1591 | .7862 | 8.381E-02 | 1.898 | .061 |
| Pair 2 | involvement of production | -1.2222 | 2.3405 | .2467 | -4.954 | .000 |
| Pair 3 | involvement of marketing | -1.2651 | 2.4796 | .2722 | -4.648 | .000 |

## TABLE 4

## The impact of involving various disciplines in the prototyping process.

| Regression analyses | Communication between design and … | | | | | |
|---|---|---|---|---|---|---|
| | Model 2h: … manufacturing | | Model 2h: … marketing | | Model 2h: … engineering | |
| | beta | s.e. | beta | s.e. | beta | s.e. |
| Intercept | ** | 0.369 | | 0.879 | ** | 0.895 |
| Physical prototyping | 0.384** | 0.115 | 0.171 | 0.307 | 0.307* | 0.313 |
| Involvement of manufacturing in prototyping | 0.360** | 0.043 | -0.234* | 0.104 | 0.127 | 0.106 |
| Involvement of marketing in prototyping | -0.141 | 0.032 | 0.389** | 0.088 | 0.016 | 0.090 |
| Adj.$R^2$ | 0.32** | | 0.20** | | 0.08* | |
| | 0.00 | N: 55 | 0.00 | N: 55 | 0.03 | N: 55 |

*Legend: * = significance level p < 0.05; ** = significance level p < 0.01; s.e. = standard error.*

## TABLE 5

## The impact of physical prototyping (PP) on organizational mode and project leader's championing.

| **Regression analyses** | **Model 3a: parallel & time orientation mode** | | **Model 3b: collaboration in balanced team** | | **Model 4: championing project leader** | |
|---|---|---|---|---|---|---|
| | beta | s.e. | beta | s.e. | beta | s.e. |
| Intercept | | 0.103 | | 0.130 | | 0.138 |
| Physical prototyping | 0.317** | 0.103 | 0.438** | 0.130 | 0.459** | 0.138 |
| Adj.$R^2$ | **0.41**** | | **0.16**** | | **0.18**** | |
| | 0.00 | N: 47 | 0.01 | N: 47 | 0.00 | N: 47 |

*Legend: *: significance level p< 0.05; **: significance level p< 0.01; s.e.: standard error; we controlled for analytical prototyping*

# TABLE 6

## The impact of physical prototyping (PP) on product concept and senior management's support.

| **Regression analyses** | **Model 5: senior management's support and attention** | | **Model 6a: product quality** | | **Model 6b: unique, surprising product** | |
|---|---|---|---|---|---|---|
| | beta | s.e. | beta | s.e. | beta | s.e. |
| | ** | 0.237 | | 0.125 | | 0.142 |
| Physical prototyping | 0.310** | 0.237 | 0.480** | 0.125 | -0.038 | 0.142 |
| Adj.$R^2$ | **0.13**** | | **0.22**** | | **0.00** | |
| p | 0.00 | N: 47 | 0.00 | N: 47 | 0.97 | N: 47 |

*Legend: * = significance level $p< 0.05$; ** = significance level $p< 0.01$; s.e. = standard error. We controlled for analytical prototyping.*

# TABLE 7

## Two-step regression analyses examining the indirect effect of prototyping on project performance.

| | **Model 7: aggregated success** | | **Model 7a: respect for time** | | **Model 7b: respect for budget & technical specs** | | **Model 7c: knowledge creation & transfer** | |
|---|---|---|---|---|---|---|---|---|
| | beta | s.e. | beta | s.e. | beta | s.e. | beta | s.e. |
| Intercept | ** | 0.230 | ** | 0.314 | ** | 0.307 | ** | 0.401 |
| Prototyping | 0.866* | 0.366 | 0.879** | 0.533 | 0.461 | 0.465 | 0.506 | 0.609 |
| Adj.$R^2$ | **0.13*** | | **0.17**** | | 0.04 | | **0.07** | |
| p | 0.040 | N: 26 | 0.009 | N: 35 | 0.153 | N: 30 | 0.063 | N: 38 |

| | **Model 7d: contribution to prestige** | | **Model 7e: respect for innovativeness** | | **Model 7f: contribution to business success** | | **Model 7g: financial, commercial success** | |
|---|---|---|---|---|---|---|---|---|
| | beta | s.e. | beta | s.e. | beta | s.e. | beta | s.e. |
| Intercept | ** | 0.373 | ** | 0.190 | ** | 0.349 | ** | 0.228 |
| Prototyping | 0.410 | 0.593 | 0.162 | 0.289 | 0.660 | 0.517 | -0.0.22 | 0.367 |
| Adj.$R^2$ | 0.03 | | 0.00 | | **0.12*** | | 0.00 | |
| p | 0.159 | N: 36 | 0.552 | N: 36 | **0.021** | N: 37 | 0.938 | N: 35 |

*Legend: * = significance level $p < 0.05$; ** = significance level $p < 0.01$; s.e. = standard error.*

## FIGURE 1

Classification of the myriad of prototypes [73].

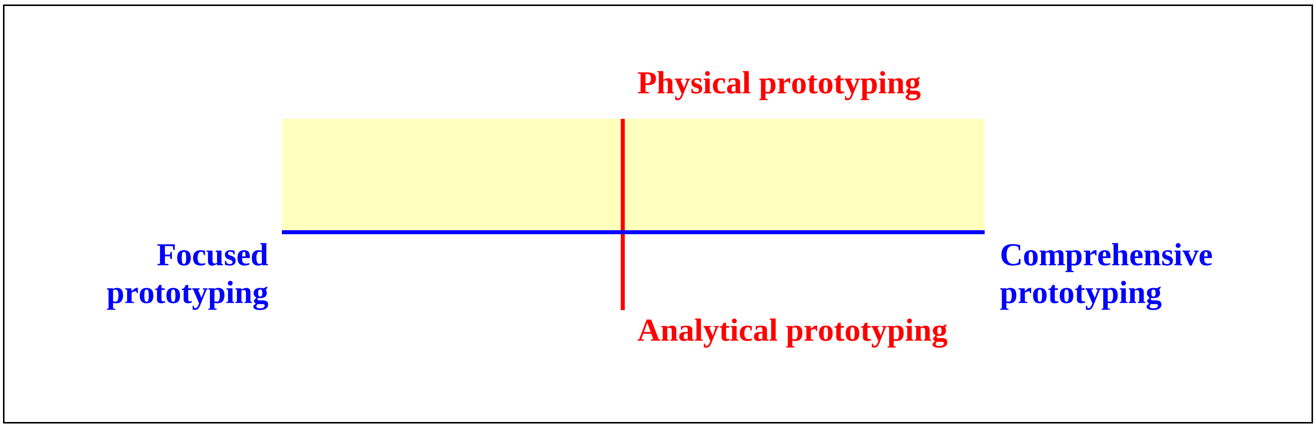

**FIGURE 2**

**The hypothesized role of physical prototyping.**