INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED11
15 - 18 AUGUST 2011, TECHNICAL UNIVERSITY OF DENMARK

EFFECTIVE SCHEDULING OF USER INPUT DURING THE DESIGN PROCESS

Young Mi Choi, Ph.D.

ABSTRACT
User input is a critical component to any product design project. Product design approaches and methods provide proven frameworks for utilizing input once it has been collected. However, these frameworks do not provide any formal mechanisms for scheduling user engagements during the course of design. This paper investigates a method based on the Design Structure Matrix which might be used to effectively schedule user engagement through the example of the design of an assistive technology product.

Keywords: User input, design process,modularity., assistive technology

1 INTRODUCTION
One of the important activities in the development of a new product is the collection of user needs and preferences. This is evident in the variety of different approaches that are utilized to gather and address them within the design process. Yet, there are a variety of factors that can hinder the effective utilization of this information during the design process. This paper will examine an example of the design of an assistive device, examine how the points for additional user input during the design of the device were identified using the Design Structure Matrix (DSM), and will discuss advantages that were observed along with potential limitations of this approach.

2 BACKGROUND
For a designer, gaining an understanding of a user's needs can be a challenge. Designers are trained to imagine themselves in the shoes of users [1]. This way, they can design as if from an end user's perspective so that the final product, ideally, performs a task in a way that works best for the user. Design decisions are based on the information at hand, so the accuracy and completeness of the need information is important.

Designers draw on their own experiences to imagine themselves in the user's place. Yet designers are not typical users. Designers tend to be experts of the device (how it is made, how it operates), while users tend to be experts at performing the task that the product is meant to help perform. This subtle difference can lead to misinterpretation of information, especially if the information is not rich enough to convey differences between a user's needs and a designer's experience.

This situation becomes more complicated in the design of an assistive technology (AT) device. A designer who is not disabled themselves may have to overcome a very wide experiential gap when designing an assistive product. They may have a descriptive understanding of a disabled user's abilities and needs but not a clear understanding of the implications of living with a functional limitation from day to day [1]. Even if the designer has a disability, he or she may not have similar personal experience to accurately relate to the target user group, such as from having the identical type and severity of limitation.

Users of AT products represent a continuum of abilities [3], from those with slight to moderate disabilities who may have more general needs to those with more severe disabilities who may have very unique and specific needs. As a result, an AT device may function well for one group of users but poorly for another group. The result of this continuum is that many markets for AT products tend to be small, niche markets [4,5]. Costs can be increased due to smaller manufacturing runs and the potential need to individualize the device during manufacture to fit the user.

The need to fit the user is important in the design of most products and particularly so in AT products. Many strategies for including users in the design process have evolved over time in an attempt to better accomplish this. These strategies generally consist of engaging users in one of three roles in the development of new products: 1) listen into to the customer domain 2) ask customers and 3) build with customers [6]. Under these categories, listening into the customer domain involves collecting needs via an understanding of the market, such as from research reports, feedback from sales people or examining sales data. Asking customers involves methods such as focus groups, surveys or interviews. Build with customers involves actively including customers in the design process during the development of solutions.

One of the main goals of each of these approaches is to accurately transfer needs information from the user, where it is typically very closely held, to the designer. Eric von Hippel [7] describes this as the stickiness of information. The stickiness of a unit of information is defined by the incremental expenditure needed to move it to a specific location so that it is in a form that is useful to the information seeker (such as a designer). When the effort required to move information is low then the stickiness is low. When the effort is high, then the stickiness is high.

One approach could be to simply involve more users more often, though this can lead to its own complications. Engaging users can be time consuming and expensive so there is a limit on how often users might be engaged. The stage of design also can make a big difference in the quality of input from users. Users are generally not very good at accurately visualizing a product from an abstract concept [8] Unless a user can see something realistic then their input will tend to be less accurate.

The catch here is that needs information can be most valuable at the beginning of the process. Design changes become more time consuming and expensive to implement the later in the process that they are discovered [9] so it is important to involve users early in the design process to help identify potential issues. But the beginning of the process is where a design will generally be more abstract, and input from users on various ideas are more likely to be inaccurate. Functional prototypes allow functionality and form to be evaluated. The user can feel and experience the product directly. Users do not need imagination to visualize features as they would if sketches, pictures or non-functional prototypes are used. Functional prototypes allow more accurate evaluations to be conducted [10] but they are often not available until much later in the process, where changes are more difficult to make.

Though direct stakeholder interaction can be critical to a designer during design it is not something that is always available. Designers are often quite separated from end users. Information is filtered by many organizational layers before actually reaching the designer [2]. For example, without modifying the method, in QFD stakeholders are only involved during the initial needs gathering to generate the design requirements [11]. The 'voice of the customer' is later represented during design by quotes and comments about particular features provided at the beginning [4]. Of course gathering needs at the outset of design is very important. This is true not only in QFD but also in other commonly used design methods such as Stage Gate [12] or Agile Development [13]. This is not surprising since, before beginning a design project, the issues to be addressed by the product should be well defined. In fact, when engaged to generate ideas users and other stakeholders will often generate far more ideas and suggestions for a product than can actually be used. This had led to the development of methods for selecting the top ideas as efficiently and reliably as possible [14].

None of these strategies clearly address how users might be efficiently engaged during design process. 'During the design' here refers to the time after the decision to develop a particular product idea has been made but before it is manufactured. Most designs proceed through several phases including Idea Generation, Concept Development, System Design, Detail Design, and Manufacture [15,16]. Idea generation is where different product ideas are considered and the best one is chosen for development based on market factors, company strategy, etc. Concept development typically involves engaging stakeholders to aid in defining the specific needs and requirements for the product. System design is where a designer or design team builds a product to meet the specifications. Detail design often involves refining user interfaces and aesthetic enhancements. A product may enter a Trial phase before Manufacture although this generally to test marketing, packaging, etc - not actual changes to the product. Outside of a customer co-creation type of process [6], users are typically involved more heavily on the front end (idea generation, needs specification) or the back end (validation and testing) of the design process. This leaves an important portion of the design process between these times devoid of input where many important decisions are made without an opportunity for further transfer or validation of information between users and designers.

3 METHOD

One possible tool that may be useful for determining how to schedule user input during a design project is the Design Structure Matrix (DSM). DSM itself is not a new tool. It was first described by

Donald Steward [17] to help find the best way to order a set of tasks based on their dependencies with each other. It has been expanded on by others such as Smith and Eppinger [18] to also be able to estimate the time needed to complete a set of tasks. This provides first an effective method for organizing tasks via a method called partitioning. This operation groups together highly interdependent tasks based on their mutual dependencies. The grouping is important for this discussion as it indicates points where the insertion of input may be useful. Second, it provides a more accurate way to estimate the amount of time necessary to complete a set of tasks.

The calculation of duration is accomplished by adding estimations of the total time needed to perform the task along the diagonal of the matrix and replacing the dependencies with the probability that the task will need to be re-worked. The resulting system of linear equations represented by the matrix can be analyzed as a reward Markov chain. This directly takes into account the effects of iteration which naturally occurs during design. Iteration arises when one the input of a first task depends on the output of a second while at the same time the input of the second task depends on the output of the first. In other words, a task A depends on B and B also depends on A. One task cannot be performed accurately without knowing or assuming the results of the other.

A project to design and build an alternating pressure wheelchair seat cushion was analyzed to evaluate the potential benefits of using DSM to aid in the scheduling of user input. The idea behind the product was to produce a seat cushion that can both dynamically alter the loading on the buttocks and control the micro-climate of the buttock-cushion interface. The microclimate is regulated by an air pump which circulates air and controls heat and humidity of the interface.

Though the basic requirements for the cushion were clearly defined, the design activities that would need to be carried out to produce the product were not. This lack of definition was one of the main problems for scheduling user engagement. The design team could anticipate some aspects of the design that would require extensive user testing and input, such as the seat cushion itself and the operational controls that the user would use to alter the loading on the buttocks when seated. However, it was not clear when this input would be required or if there were other important aspects of the design which might require or benefit from additional input during the design process.

The key members of the design team were engaged in order to bring more definition to these tasks. The team members who participated in this exercise were the lead engineer in charge of the electronics, the lead engineer in charge of designing and fabricating the physical systems of the product, the project manager leading the design team and finally the director overseeing the cushion development as well as other initiatives. The first step was to define the tasks that were anticipated in order to develop the required functions. These design team members were first interviewed as a group in order to define these. Each design team member came to the meeting prepared to lay out the tasks that were needed from their perspective. This process took two separate meetings lasting approximately two hours each.

After the tasks were defined, the next step was to identify all of the dependencies between the tasks, the likelihood of re-work, and estimated task duration. The tasks were laid out in a DSM-like square matrix prior to meeting the design team members. Each team member was met individually and asked to sequentially review each of the tasks defined on the left-hand side of the matrix and mark any dependency that the task had on any. This was done by placing a “1” in the column corresponding to the dependent task. Next, the re-work probability was estimated. To do this, the team member reviewed each of the dependencies in the matrix. Each “1” was replaced with a decimal value between 0 and 1 corresponding to the percent chance that the task might need to be re-executed based on the output of the dependent task. Finally, the team member was asked to estimate how long it would take to perform the design task by itself (with no re-work). This value was defined in days and placed along the diagonal for each task.

The dependencies, re-work probabilities and task durations in the matrix were used when interviewing the next team member. The same exercise of defining dependencies, probabilities and task duration was performed. Any new dependencies were added directly to the matrix. If any disagreement or questions about existing values arose, these were recorded separately and the disagreement highlighted in the matrix by highlighting the cell. After each member was interviewed individually, the team was interviewed again as a group in order to resolve the discrepancies found in the individual interviews. For each difference, the group discussed and agreed on an appropriate value which was then entered into the task matrix.

4 RESULTS

DSM analysis was performed on the completed matrix. The partitioning function was performed using an excel macro found on the Design Structure Matrix homepage (http://www.dsmweb.org). This identified the groupings of highly related tasks. The reward Markov analysis was performed using a program written to implement the heuristic search described by Smith and Eppinger. This step performed two functions. It allowed the duration of a set of tasks to be calculated and it also allowed rearrangement of the specific set of tasks into the most efficient order (least time required) based on the task dependencies, re-work probabilities and durations.

There were a wide range of possible times for each of the groups of tasks, depending on the order in which they were arranged. The heuristic search program was designed to keep track of the longest and shortest of the orderings during the search. Each of the main groups of tasks was given a name for ease of reference. For example, the first task group in Table 2 consisted of the tasks required in order to determine the specific properties of the internal and external materials:

- Determine outside material type
- Determine foam type (reticulated vs typical)
- Determine foam stiffness
- Determine foam density
- Determine foam heat conductivity

The least efficient ordering along with most efficient ordering calculated during the analysis are shown in Table 1.

Table 1. Execution time of best and worst task orderings evaluated by the heuristic search.

Task Group	Worst Ordering (days)	Best Ordering (days)
1. Bladder material properties	18.6	12.5
2. Internal foam and cover material properties	27.8	23.4
3. Design major mechanical components	45.5	38.2
4. Electronics and mechanical component integration	136.5	123.2
5. Design control hardware and interface with electronics	23.2	18.4
6. Design occupancy switch	16	16
7. Software program design	49	49
8. Design heat sink base	98.3	87.3
9. Cushion cover features	2.3	2.1
10. on/off switch features	4.8	4.5
Total	**422**	**374.6**

5 DISCUSSION

The DSM analysis of the seat cushion project show several potential advantages to this approach. The first of these is simply the potential reduction of the time needed to perform a project by properly ordering the tasks. Ordering tasks within blocks differently can lead to a difference of 47.4 days, or just over 11%. At the time of this analysis, it was an ongoing project. Close inspection shows that two of the blocks, “Design occupancy switch” and “Software program design”, are actually single tasks. Both of these, particularly the software design, would almost certainly require more than one task to perform which may have dependencies on existing tasks. This does not necessarily pose a problem since tasks within the larger blocks have dependencies on one another as well. Non iterative dependencies will tend to move the entire block earlier or later in relation to the others.

Another advantage, particularly important to this project, is that the analysis gives an indication of the best times to potentially solicit input from users. Recall that users are not particularly good at imagining and providing accurate opinions on imagined objects. But if users are engaged at the completion of a module, the required design tasks will be completed and there can be a concrete artifact for the user to evaluate. In this example a user might to provide direct feedback on the foam and cover materials that are chosen or the operation of the pump and mechanical components after they have been integrated. This provides the design team with necessary input at the time it is actually needed so that the solution can be best fit to the need.

Because the overall time for each module can be estimated, intelligent decisions (based on cost, available time, etc) can also be made on the quantity of input to be solicited during design. In this case it may not make much sense to engage users immediately after designing the major mechanical components. They are unlikely to be very comprehensible to a user until after the next set of tasks that integrate the electrical and mechanical components with one another. It would make sense to ensure that an evolving solution is acceptable to users at this point before continuing on to later tasks. If a check is not made, say, until after the software design is complete, if a major problem with the hardware components or integration is discovered it may require each step that comes after the problem task to be re-executed to resolve the problem.

After the analysis was performed in this case, some additional areas for input were identified. It became clear that input after completing the second task group would be useful. This would ensure that decisions made to satisfy the technical requirements (internal bladders, internal and external materials) were also acceptable to users. This would allow acceptable changes to be made before later tasks were performed which depended on the attributes of these decisions. It was also clear that the occupancy switch would be a good time for additional input. The occupancy switch is the system that automatically detects the presence of a user and initiates the pre-programmed operation of the cushion. In both of these cases, the additional input was felt necessary due to the large number of dependencies of later tasks. In other words, if these components were not designed in a way that was acceptable to the end users, then any problems requiring them to be re-worked would set off a kind of chain reaction requiring all of the later tasks to be re-worked as well.

The initial partitioning organizes tasks into groups roughly corresponding to modules within the design. A modular design, where modules are parts of a larger system that are independent of one another but work together [19] is highly desirable. Breaking a problem down into smaller independent pieces reduces the overall complexity of the problem and makes the individual pieces easier to solve [20]. This proved to be very useful in this project. The tasks, although relatively high level, were specific enough to clearly define all of the steps that must happen during design. This of course is helpful from a management standpoint (not only for identifying when to begin planning for input but also for things like design resource allocation). It was also helpful from a design planning perspective. The general architecture of the product had been defined prior to the defining the individual design tasks. However, defining the design tasks in conjunction with all of the major decision makers allowed discussion and consideration of different approaches for implementation. During the group meetings after the task dependencies, re-work probabilities and task durations had been defined, some further discussion of task definition took place. The focus was on reducing, as much as possible, dependencies that were above the diagonal in the matrix. These denote iteratively dependent tasks and wherever these could be removed by re-defining the task plan, the more serial and less complicated the design plan would be. Great focus was not placed on this activity, however minor changes in approach were agreed upon which removed some unnecessary inter-dependencies.

There were opportunities for further re-evaluation for further simplifications, though it would have required additional planning meetings that were not allowed for due to time constraints. It is entirely possible that the same problem could be approached in a different way. This in turn would result in a very different set of tasks and modules. Of course DSM by itself does not help in analyzing and breaking down a particular problem. However since the basic tasks and dependencies needed to implement a design are identified during analysis of the problem, DSM could be very useful in understanding the impact that different design approaches may have on the overall project if they are mapped out during the early phases of the process.

Accuracy of the estimation of overall duration is clearly a potential issue with this approach. The estimations of both the individual task durations and the likelihood of iteration will have a significant impact on the analysis. The product in this example was new to the world in nature (it was not an update to an existing product) the task durations and re-work probabilities are likely much less accurate than they would be if an already existing product were being updated. The estimated duration would likely be much more accurate as the analysis would benefit from knowledge of duration and re-work gained from the previous design. Most new products are incremental in nature

[21] so the potential for accurate predictions for existing designs seems high. This analysis also only considers sequential development. Iteration resulting from executing tasks in parallel has also may also be analyzed within DSM [22]. Real design is neither completely parallel (as in this analysis) or completely sequential, the parallel approach for analysis seems best suited as it more closely resembles the way that design tasks are typically organized and actually managed.

Finally, this type of DSM analysis might be usefully applied with a wide range of existing design methods. Organizations learn how to do things better over time. This organizational learning includes a company's the managerial and technical systems that make up an organizations values [8]. This internal knowledge is one of the things that help to provide companies with competitive advantages within particular markets. Large changes to these workings can undermine these advantages. For example a company that utilizes a method such as QFD for engineering design will not likely adapt easily to adopting a fully customer co-creation type model. A DSM type approach might be used during early project planning in addition to existing; proven processes so that more direct customer involvement might be included in a useful manner.

6 CONCLUSION

Analysis of a design project via DSM appears to have a number of advantages to the management of design in general and AT design in particular. It can be used to estimate the actual time needed to perform the tasks in a design project with the effects of re-work included. It may also be used as a planning tool to investigate the impact that different design approaches may have on the overall project. Finally, it can be used to optimize the task orderings of a design project and indicate specific points where additional user engagement may be useful so that intelligent decisions can be made on how much input is needed. This can aid not only in identifying problems earlier in the deign process but will also give designers the opportunity to engage users in a timely manner to ensure that the solution truly addresses their needs.

REFERENCES

1. Nieusma, D. (2004). "Alternative Design Scholarship: Working Toward Appropriate Design." *Design Issues* **20**(3)
2. Norman, D. (1988). *The Design of Everyday Things*. New York, Basic Books.
3. Cook, A. and S. Hussey (1995). Assistive Technologies: Principles and Practice. St. Louis, Mosby
4. Harwin, W. S. (1998). *Niche Product Design, a New Model for Assistive Technology*. Technology for Inclusive Design and Equality (TIDE), Helsinki
5. Cowan, D. and A. Turner-Smith (1999). The Role of Assistive Technology in Alternative Models of Care for Older People. *With Respect to Old Age: The Royal Commission for the Long Term Care of the Elderly*. I. Sutherland. 2.
6. Piller, Frank T., Ihl, Christoph and Vossen, Alexander, A Typology of Customer Co-Creation in the Innovation Process (December 29, 2010). Available at SSRN: http://ssrn.com/abstract=1732127.
7. von Hippel, E. (1994). ""Sticky Information" and the Locus of Problem Solving: Implications for Innovation." *Management Science* 40(4).
8. Leonard-Barton, D. (1992). "Core Capabilities and Core Rigidities: A Paradox in Managing New Product Development." *Strategic Management* 13(1).
9. McGrath, M. E., M. T. Anthony, et al. (1992). Product Development: Success Through Product and Cycle-time Excellence, Butterworth-Heinemann.
10. Page, A. and H. Rosenbaum (1992). "Developing an Effective Concept Testing Program for Consumer Durables." *Journal of Product Innovation Management* 9(4).
11. Kaulio, M. A. (1998). "Customer, consumer and user involvement in product design; A framework and review of selected methods." *Total Quality Management* 9(1).
12. Cooper, R. G. (1990). "Stage-gate systems: A new tool for managing new products." *Business Horizons* 33(3).
13. Beck, K., M. Beedle, et al. (2001). "Manifesto for Agile Software Development." from http://agilemanifesto.org/.
14. Toubia, O. and L. Flores (2007). "Adaptive Idea Screening Using Consumers." Marketing Science 26(3): 342-360.
15. Cross, N. (1994). Engineering Design Methods: Strategies for Product Design. West Sussex, John Wiley & Sons Ltd.

16. Ulrich, K. and S. Eppinger (2003). Product Design and Development. New York, McGraw Hilll
17. Steward, D. V. (1981). "The Design Structure System: A Method for Managing the Design of Complex Systems." *IEEE Transactions on Engineering Management* 78(3): 71-74.
18. Smith, R. and S. Eppinger (1997b). "Identifying Controlling Features of Engineering Design Iteration." *Management Science* 43(3): 276-293.
19. Carliss Y. Baldwin, K. (2000). Design Rules: The power of modularity. Caimbridge, The MIT Press.
20. Alexander, C. (1964). Notes on the Synthesis of Form. Massachusetts, Harvard University Press.
21. Levitt, T. (1966). "Innovative Immitation." *Harvard Business Review* 44(5).
22. Smith, R. and S. Eppinger (1997a). "A Predictive Model of Sequential Iteration in Engineering Design." *Management Science* 43(8): 1104-1120.