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Application of the Design Structure Matrix to Wheelchair Development

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Abstract

Wheelchair users with brain-related problems experience involuntary extensor thrusts, which may cause injuries due to unexpected impacts with the wheelchair. An improved wheelchair design would be very beneficial to such users. This paper uses the Design Structure Matrix (DSM), which is an information exchange model that helps find the relationship between tasks in a product development process in order to minimize development time. This is the first application of the DSM to wheelchair development for people with extensor thrust. Numerical evaluation methods are presented to provide the optimal ordering of groups of design activities.

Keywords
Product Development, Extensor Thrust, Design Structure Matrix, Wheelchair Design

1. Introduction
The medical field benefits from product development (PD): technological advances allow patients to benefit from more accurate devices to diagnose their conditions. Reducing PD time is a critical factor for producing highly competitive products. The PD process consists of many interrelated phases that aim to develop products to satisfy market needs [1]. However, PD projects contain many complex tasks that make most of the traditional project management methodologies such as CPM, PERT, and GERT fail in managing the iterative nature of the tasks inherent in PD [2-4]. To manage and analyze complex products, the Design Structure Matrix (DSM) has been developed [5]. The DSM method is an information exchange model as it can analyze the interactions among the elements of a decomposed product. Also, it can be effectively used to resolve the iteration problem, which occurs due to changes in input information, updates of shared assumptions and fault discovery in the design process [6].

This paper studies the use of PD techniques in the medical field. Most medical products are characterized by their complexity and sensitivity. One such product is the wheelchair. Most disabled people use the wheelchair in their daily life. Most current wheelchairs are rigid systems and cannot adapt to human behaviors. Therefore, developing a wheelchair that can deal with human needs and study movements is a challenging problem. Recently, research has shown that using a dynamic seating system can help to provide more freedom to the person and reduce the generated forces between the wheelchair and the user [7]. More specifically, some disabled people have unbalanced movements because their brains do not have enough control on their body muscles. This phenomenon is called high-tone extensor thrust; it is a non-contagious reflex which occurs when the extensor muscle group forces the body into a straightened position. Due to brain disorders that propagate during the birth period, it becomes difficult for the disabled person to control his/her muscles tone. This involuntary and unexpected event causes an undesirable and hurtful position for the person. Thus, sitting would be impossible unless the patient is forced into flexion. Very little research work has been done in developing wheelchairs for people with high extensor thrust [7-10]. Recently, the feasibility of using a dynamic seating system as a solution for people with the extensor thrust has been studied. An experimental system that is capable of identifying the human-generated forces during unconstrained extensor thrust has been developed [8]. Some concepts for the dynamic seating system have been suggested such as a Seatback Rigidizer concept and a variable-stiffness support surface concept [8, 9]. This paper discusses the use of the DSM method in managing and analyzing the dynamic seating system that is capable of controlling extensor thrust. This method provides an efficient sequence of the design activities and an estimation of the total design time.

2. Literature Review

Many researchers have developed models to reduce PD lead time [11-15]. Other studies of PD use a matrix form in modeling the PD process. The DSM method was developed to analyze and manage the activities of any complex system [5, 16]. Also, it was used to capture and manage the system-level design knowledge [17]. Many researchers have developed DSM models in order to solve the iteration problem in the PD process [18-20]. The DSM analysis can clarify where to concentrate efforts to speed the process and improve the ways of developing products [6, 21]. In this paper, the DSM is applied to the development of an active dynamic seating system for people who exhibit extensor thrusts.

3. Design Structure Matrix

The DSM is a square matrix that consists of identical rows and columns that represent the design activities and the relationships among them. By using this method an efficient sequence of the design activities can be achieved. Also, the DSM method can provide a good estimation of the total design time of the wheelchair. Component-based DSM is used in this work: it is a static model representing the components of a product and shows interactions between elements in a complex system. Any product consists of tasks or components. Those tasks or components are listed along the row headings and column headings of the matrix in the same order. If there is no information transformation, the shared cell between those tasks is left empty. If any task from a row gives information to the other task in the column, an X mark is put inside their cell. In the coupled relationship, the flow of influence or information is intertwined. Several approaches are used in DSM partitioning and tearing [5, 14]. Partitioning is the process of manipulating the DSM rows and columns so that any feedback marks should be eliminated or moved toward the diagonal by transforming the DSM into a lower triangular form resulting in a faster development process. Tearing is the process of reducing the number of feedback marks or "tears" from the matrix in order to convert it to a lower triangular matrix. After identifying these tears, the matrix is repartitioned. PSM32 is special software designed to model the design processes by reordering and tearing the DSM rows and columns. A numerical DSM can provide more detailed information on the relationships between the different system elements. The Work Transformation Matrix (WTM) is used to tackle design iterations efficiently and contains the strength of dependency between the tasks and determines the rate and nature of the convergence of the design process deterministically.

4. Wheelchair Design

With medical and technological advances, wheelchair users can choose from a large type of wheelchairs. However, disabled people with extensor thrusts are one segment of the wheelchair population who need special care and attention, and face many difficulties while driving their wheelchair. Most wheelchairs currently on the market do not address their needs. During an extensor thrust the body tends to straighten out to a prone position. The goal of the research described here is to develop a dynamic seating system for extensor thrust phenomenon using the DSM method. The design is adapted from [9], which was designed and developed to reduce the forces generated during extensor thrusts using the concept of a variable-stiffness support surface. An active dynamic seating system with a single-hinged seatback was developed to collect real data necessary for studying the human body forces [22].

5. Dynamic Seating System Development

In this section, the application of the DSM in the design of a Dynamic Seating System is discussed. A general DSM methodology is used for every sub-system of the wheelchair and then the whole assembly design of the seating system is created. The structure of a seating system can be broken into three main sub-system structures as follows: Seat Back, Seat Bottom, and Foot Rest. The seat back consists of 18 main components and its design should be rigid enough to support the occupant's body. The seat bottom consists of 11 main components, and uses a variable stiffness concept similar to the seat back. The footrest system consists of 11 components and depends on two degrees of freedom: knee rotation and shaft elongation. Table 1 shows the main seating system components. The information flows among components are identified and the whole DSM is constructed as shown in Figure 1.

5.1 Partition and Tearing the DSM to Analyze the Design Process

Once the original DSM is created, partitioning and tearing the DSM can be done using the software PSM32 to optimize the sequence of design elements and convert the matrix into lower triangular form. Figure 2 shows the new DSM after partitioning, containing ten blocks. The best ordering can now be found. The design can be started from the control box (11). The three couples: (14, 15), (4, 12), and (5, 6) can be executed concurrently. These couples contain iterative work. For example, the couple (4, 12) means that the support rails and spilt rubber washers depend on each other. Components 19 and 24 can also be executed before the couple (5, 6).

Table 1: The Seating System Parts

Symbol	Part Name	Symbol	Part Name
1	Roller Wheel	**21**	Pivot Bar
2	Tension Support Bars	**22**	Rigitizer Bar
3	Frame Rods	**23**	Moving Flexure Bar
4	Support Rails	**24**	Seat Bottom Limit Switch
5	Motor	**25**	Seat Support Frame
6	Motor Mount	**26**	Lever Arm_1
7	Linear Bearings	**27**	Lever Arm_2
8	Interface Plate	**28**	Clamps
9	Support Framework	**29**	Seat Cushion
10	Toothed Drive Belt	**30**	Upper Magnet Support Bar
11	Controller Box	**31**	Lower Magnet Support Bar
12	Spilt Rubber Washers	**32**	Footrest Connector
13	Seat Back Limit Switches	**33**	Permanent Cup Magnetic
14	Seat Back Magnets	**34**	Right Coupling Bar
15	Magnets Attachments	**35**	Right Footplate
16	Flexible Backrest	**36**	Right Internal Spring
17	Seat Back Plate	**37**	Right Footrest Shaft
18	Seat Back Bracket	**38**	Right Spring-damper
19	Seat Bottom Hinge	**39**	Left Footplate
20	Linear Actuator	**40**	Wheels

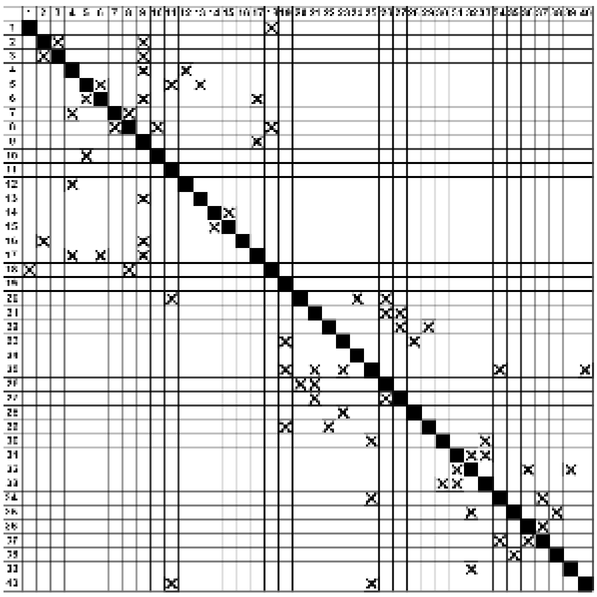

Figure 1: The Original DSM of Seating System Design Assembly

When components 11 and 24 are carried out, the third block can be sequentially executed. The suggested ordering inside this block is 20, 21, 26, and finally component 27. If the information of any component is known, the iteration should be removed from the block, thereby reducing the overall execution time. Then, three couples: (23, 28), (2, 3), and (22, 29) can be executed in parallel. After that, the footrest shaft block is executed. To build the seat back subsystem, the seat back roller assembly is executed sequentially with the toothed drive belt component. The suggested ordering of this block is as follows: roller wheel, linear bearings, interface plate and then the seat back bracket. Footrest magnet block is executed concurrently with the seat back roller assembly. The last block is the right footplate assembly which consists of two components: right footplate and right spring damper. The shared parts are the control box and the human body, which means that the system will be converted from the rigid state to the dynamic one or vice versa, voluntarily or involuntarily. The DSM shows that the critical path can be found by finding the longest path between the three systems. This means they are executed concurrently with different teams, assuming the teams work in close proximity with fixed membership. Next, the minimal design time and optimal ordering of the tasks are found.

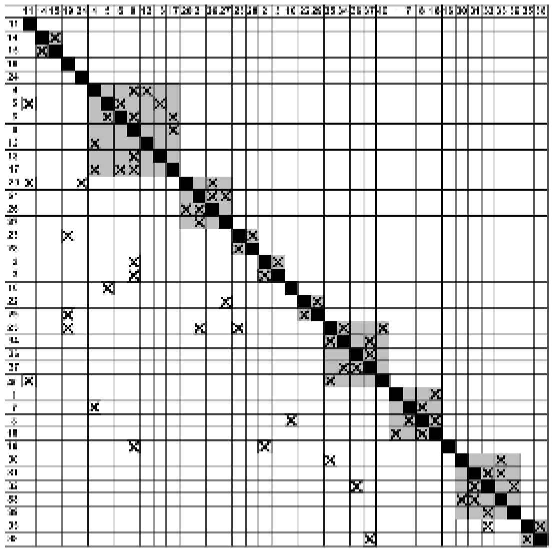

Figure 2: The Partitioned DSM

6. Numerical Evaluation of the DSM

In this section, the minimum design duration of the seat back system is computed using two numerical methods.

6.1 Calculation of the Minimal Length Order of the Block

The total design assembly can be found based on the length of time of each block. From Figure 2, the roller wheel assembly block is chosen for sample calculation. This block contains tasks 1 (A), 7 (B), 8 (C) and 18 (D), as shown in Figure 3.

		Component	A	B	C	D
1	A	Roller Wheel	4	0	0	0.3
7	B	Linear Bearings	0	5	0.1	0
8	C	Interface Plate	0	0.2	7	0.1
18	D	The Bracket	0.1	0	0.1	2

Figure 3: 4 × 4 Numerical Design Structure Matrix

The diagonal values of the DSM give the duration for components A, B, C, and D if done in isolation. The off-diagonal values correspond to probabilities, and have values of between 0 and 1. If the probability, p_{ij}, is greater than 0 where $i \neq j$, it means that the ith task should be repeated, given that there are new results coming from the jth task and can affect the ith task. Thus, these probabilities are replaced in the off-diagonal blanks. Also, the empty blanks mean that there is no work required between the tasks and therefore they should be filled with 0s. Hence, the execution process for the sequence A-B-C-D should be divided into four stages based on the reward Markov chain, as shown in Figure 4. Every task is carried out at each stage.

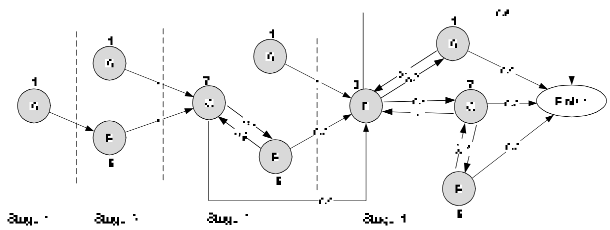

Figure 4: Reward Markov Chain for ABCD Ordering

The expected time to finish each task is the sum of the task time itself, plus the probability of reworking the other tasks. So from the matrix the following linear equations can be defined.

$$Q_A = 0.1Q_D + 4 \tag{1}$$

$$Q_B = 0.2Q_C + 5 \tag{2}$$

$$Q_C = 0.1Q_B + 0.1Q_D + 7 \tag{3}$$

$$Q_D = 0.3Q_A + 0.1Q_C + 2 \tag{4}$$

where Q_I represents the expected time remaining of task I in stage 4, and $I = A$, B, C and D respectively. The four equations can be written in matrix form and solved to give Q_D equal to 4.131 that should start at stage 4. After that, the expected time remaining of P_C for stage 3 is calculated. Again, the following equations represent the three stages without stage 4.

$$P_A = 4 \tag{5}$$

$$P_B = 0.2P_C + 5 \tag{6}$$

$$P_C = 0.1P_B + 7 \tag{7}$$

where P_J represents the expected time remaining at each node J in stage 3. Thus, the solution is P_C = 7.653. Finally, T_A = 4 and S_B = 5. The total execution time of the block function is the sum of the time remaining in each stage: Q_D+ P_C + S_B+ T_A = 4.136+ 7.653+ 5 + 4= **20.784**. Similar to the above calculation of the sequence A-B-C-D, all possible sequences of the tasks in the block can be determined. The minimal length ordering is 19.351 from the sequence DBCA or BDCA, and the longest execution duration is 21.678 from the sequence CADB or ACDB. The optimum sequence that may decrease the design changes is first designing the brackets or the bearings, then designing the interface plate and finally the Roller. The minimum ordering is 12.03% shorter than the longest one.

6.2 Determination of the Eigenvalues and Eigenvectors for the WTM

In this section, the effect of the coupled tasks on the total roller wheel assembly design time using the WTM model is introduced. Matrix A is considered to calculate the total design work for the block. The off diagonal entities show all rework probabilities and the diagonal values are 0's values. By decomposing the matrix, the diagonal matrix Eigenvalues Λ and the corresponding eigenvector matrix S are calculated:

$$A = \begin{bmatrix} 0 & 0 & 0 & 0.3 \\ 0 & 0 & 0.1 & 0 \\ 0 & 0.2 & 0 & 0.1 \\ 0.1 & 0 & 0.1 & 0 \end{bmatrix} \qquad \Lambda = \begin{bmatrix} 0.2175 & 0 & 0 & 0 \\ 0 & -0.2175 & 0 & 0 \\ 0 & 0 & 0.1126 & 0 \\ 0 & 0 & 0 & -0.1126 \end{bmatrix}$$

From the eigenvector matrix, the values of the work vectors can be calculated as follows:

$$u_0 = \begin{bmatrix} 1 & 1 & 1 & 1 \end{bmatrix}^T \tag{8}$$

$$u_1 = \begin{bmatrix} 0.3 & 0.1 & 0.3 & 0.2 \end{bmatrix}^T \tag{9}$$

$$u_2 = \begin{bmatrix} 0.06 & 0.03 & 0.04 & 0.06 \end{bmatrix}^T \tag{10}$$

$$u_3 = \begin{bmatrix} 0.018 & 0.004 & 0.012 & 0.010 \end{bmatrix}^T \tag{11}$$

Thus, three measures can be used to rank the design modes as follows. First, calculating the term $(I - \Lambda)^{-1}$ followed by total weight of the eigenvector, the total work vector U is:

$$U = S(I - \Lambda)^{-1} S^{-1} u_0 = \begin{bmatrix} 1.391 & 1.105 & 1.325 & 1.274 \end{bmatrix}^T \tag{12}$$

Based on the magnitude of the terms $(I - \Lambda)^{-1}$ and the total work vector U, the four tasks are ranked from the least contribution to the largest contribution as BDCA and this sequence is optimum and takes the minimal design time.

7. Conclusions

In this paper, the DSM method was applied to the development of an active dynamic seating system for people with extensor thrusts. The main benefit of this research is its contribution to wheelchair development, as well as developing an efficient device capable of studying an extensor thrust event. Furthermore, the research has provided a detailed application of the DSM tool in planning and designing a product. The DSM helps to model and manage the design process by sequencing the design tasks and reducing the total duration. It has proven to be an effective tool in PD. This research has certain limitations: the DSM method depends on the opinions of the team members. This means that this process is prone to human and calculation errors. Also, it does not provide the optimal solution in PD process; rather it can be used successfully as a guide of the design process. Further research should consider using different methods, such as optimization techniques to give some support to the DSM tool in deciding the best tasks sequence. This research only focuses on the component DSM type. Other types such as parameter DSM type should also be developed so that more important information and interactions of the project can be provided.

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