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A SELECTIVE DISASSEMBLY METHODOLOGY FOR END-OF-LIFE PRODUCTS

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ABSTRACT

Disassembly planning has become an important strategic issue in order to reduce the environmental impact and increase the value of end-of-life (EOL) products. However, disassembly could be costly due to the uncertainties involved in the process such as process complexities and alterations, hence, finding an optimum disassembly sequence is an important issue that needs further attention. In this paper, a selective disassembly methodology for EOL products is presented, which was developed by modifying the methodology developed by Nevins and Whitney (1989) for assembly. A Java-based computer program has been developed to carry out the disassembly sequence generations and the winnowing process. A single-hole punch was used as a case study to explain the concept and the efficiency of the methodology. The major advantage of this methodology is to provide a graphical representation of disassembly sequences at different stages of the process, which allows the user to visualise the disassembly process. As one expects, once the product under investigation becomes complex, the number of liaisons, and consequently the generation of all possible disassembly sequences becomes a tedious process. The proposed methodology will speed up this process, and in addition, an expert system is being developed to make the judgemental process of winnowing faster and easier.

KEYWORDS

Sustainable manufacturing, End-of-life options, Selective disassembly, Winnowing

INTRODUCTION

Since sustainable manufacturing has become a challenging global issue in the manufacturing area, a wide range of research has been carried out to deal with the more effective use of natural resources and the reduction of environmental impacts during the product life cycle, while still meeting customer's demands for high quality and affordable products. A key-point in these research activities is the disassembly of the end-of-life (EOL) products, which is necessary to minimize the environmental impact of discarded products and to better utilise their materials. Disassembly may be defined as "a systematic method for separating a product into its constituent parts, components and sub assemblies" (Gungor and Gupta, 1999). Disassembly should not be considered as the reverse of assembly due to the following reasons:

- *Different operations*: the reversing of assembly sequences is often very difficult and unprofitable, and destructive operations may be necessary;
- *Different targets*: a "disassembly depth" has to be determined in order to maximize profits and to minimize the environmental impact;
- *Product conditions*: components to be disassembled are often damaged, corroded, etc.

Disassembly plays a key role in EOL decision making as shown in Figure 1. As a result, disassembly planning has become an important strategic issue. Consequently many research articles have been published on disassembly planning, which determine the product representation in disassembly planning (Subramani and Dewhurst, 1991; Yokata and Brought, 1996; Qian and Pagello, 1994; Laperriere and ElMaraghy, 1992; Zussman et al, 1994; Feldman and Scheller, 1994; Mascle, 1998), task analysis and representation (Mattikalli et al., 1990; Bhaskare, 1993; Kroll, 1996; Sanderson, et al., 1988) sequencing and clustering, disassembly scheduling, disassembly processes and operations (O'Shea, Kaebernick, Grewal, 2000). On the other hand, there is very little research being carried out in area of "selective disassembly", which requires the disassembly of selected

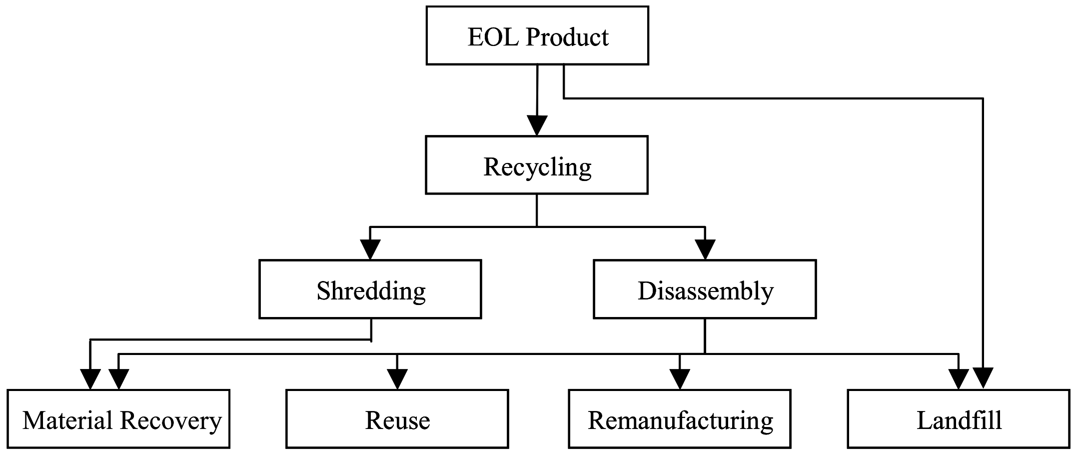

Figure 1. The role of disassembly in EOL decision making (Zussman et al., 1994).

the components with reuse potential (Srinivasan et al, 1998; Srinivasan and Gadh, 1998). The aim is to determine a disassembly sequence for these selected components with minimal removal of other components. However, these analyses are usually time consuming and expensive because of the high number of possible disassembly sequences (Santochi et al, 2002).

In this paper, a selective disassembly methodology for EOL products is presented, which was developed by modifying the methodology by Nevins and Whitney (1989) for assembly. A Java-based computer program, which is not described in this paper, has been developed to carry out the disassembly sequence generations and the winnowing process. A single-hole punch was used as a case study to explain the concept and to demonstrate the efficiency of the methodology.

METHODOLOGY

As mentioned earlier, it is not suitable to consider disassembly as the reverse of assembly. However, it is possible to adopt some basic principles of assembly planning and apply them to disassembly. Therefore, the basic planning steps used by Nevins and

Whitney [1989] for assembly planning have been adopted and modified for disassembly. The proposed steps for disassembly are shown in Figure 2.

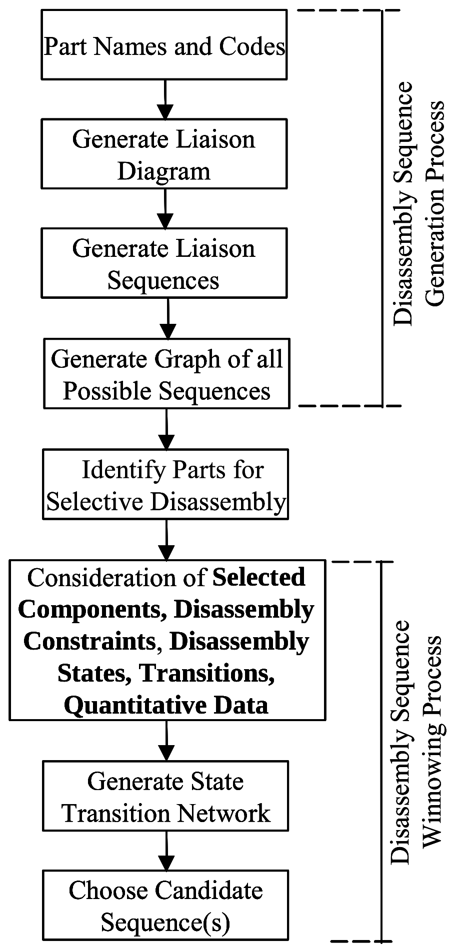

Figure 2. Steps of generating a selective disassembly sequence.

The steps are generating a liaison diagram, establishing precedence rules, generating all possible disassembly sequences, and carrying out a winnowing process to select the most feasible disassembly sequence(s). In the next section, a one-hole punch will be used as an example product to explain the methodology and to demonstrate the efficiency of the methodology.

APPLICATION: A SINGLE HOLE PUNCH

In order to demonstrate the methodology, a one-hole punch is selected. The same product was used by O'Shea (1999) to demonstrate a different disassembly planning approach. By using the same product and the same data, it can be shown that the proposed sequence planning approach leads to the same results. Figure 3 shows the exploded and assembled view of the one-hole punch.

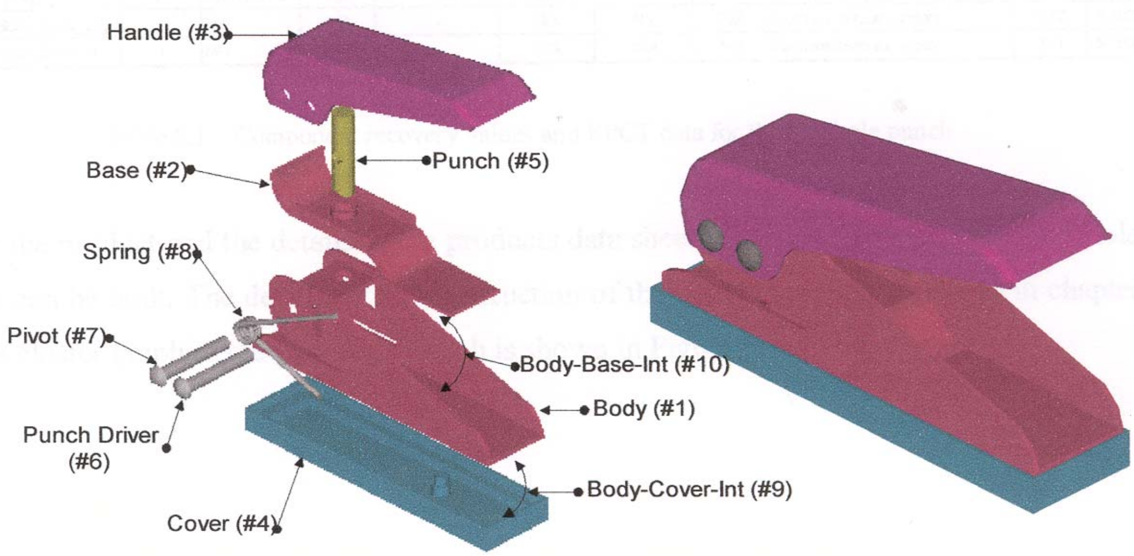

Figure 3. Exploded and assembled view of the one-hole punch [O'Shea et al., 1999].

For the purpose of this study, it is assumed that the product is disassembled in a manual workcell. The components within the one-hole punch are indicated by the number pointing to them. In addition, two more components are identified within the product, these are component #9, the intangible fastening agent between the Body (#1) and the Cover (#4), and component #10, the intangible fastening agent between the Body (#1) and the Base (#2).

The first step in creating the disassembly sequence is to create the part listing and their designated EOL options as shown in Table1.

Part Code	**Part Name**	**Material Type**	**End Use**
A	Pivot (#7)	Scrap Steel	Recycle
B	Handle (#3)	Scrap Steel	Recycle
C	Body (#1)	Scrap Steel	Recycle
D	Spring (#8)	Spring Steel	Reuse/Remanufacture
E	Punch Driver (#6)	Scrap Steel	Recycle
F	Punch (#5)	Tool Steel	Reuse/Remanufacture
G	Base (#2)	Scrap Steel	Recycle
H	Cover (#4)	Plastic	Recycle

Table 1. One-hole punch part listing and their EOL use (O'Shea, et al., 1999).

Then, the liaison analysis is carried out by using original assembly drawings and the expert input to generate the liaison diagram of the product. According to the part list and exploded drawing of the product, the liaison diagram is generated to illustrate the connection between parts as shown in Figure 4. The liaison diagram shows a network of nodes and lines that represent the parts and the relationships between parts termed as liaisons respectively. In this case, there are 12 liaisons for the one-hole punch. Thus, the function of a liaison in the disassembly sequence diagram is to detach the connection between parts to which this liaison refers.

The analysis continues by determining the precedence relations for each liaison, which then form the basis for generating the liaison sequences. The precedence relationships are established by answering two questions for each liaison: (1) Which liaison(s) need to be done already to allow doing liaison *i*? (2) Which liaison(s) need to be undone to allow doing liaison *i*? The answers to these questions yield a set of precedence rules, which present the prerequisite actions for establishing each liaison.

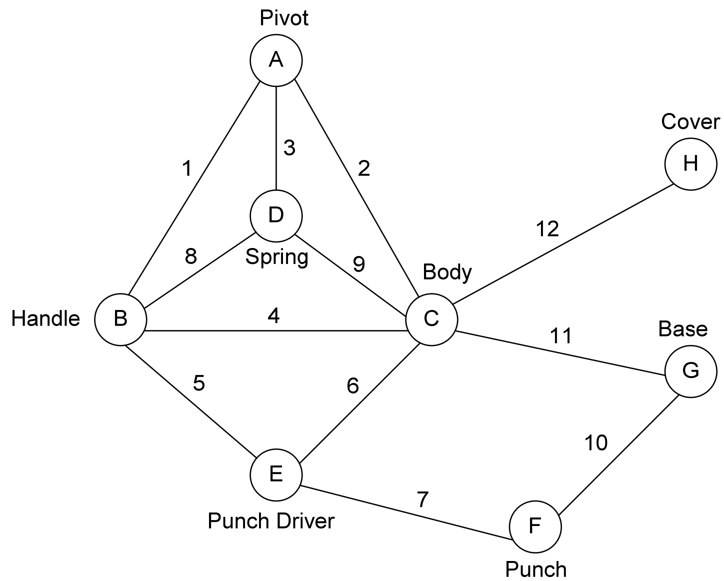

Figure 4. Liaison diagram for the one-hole punch.

Moreover, this rule set confines the extent of disassembly sequence generation and directs the disassembly moves. Since the precedence rules are the most important basis for the sequence planning, the establishment of the rules for the one-hole punch is described in the following:

- ***L_1 (Pivot-Handle):***

The pivot can be detached from the handle straight away since both parts are accessible from the outside of the punch. Therefore, L_1 requires no prerequisite action.

- ***L_2 (Pivot-Body):***

Once the pivot is withdrawn from the handle, it can be released from the body. The answer to this question yields the precedence rule of liaison 1 (L_1) must be done before liaison 2 (*L2*). In shorthand writing, this can be represented as $\{L_1 \rightarrow L_2\}$.

- ***L_3 (Pivot-Spring):***

To remove the pivot from the spring, it must be withdrawn from the handle as well as the body. This forms the rules $\{L_1, L_2 \rightarrow L_3\}$.

- ***L_4* (Handle-Body):**

There are two alternative disassembly paths that lead to the disconnection between the handle and the body, either removing the pivot from the handle, the body and the spring or withdrawing the punch driver from the handle, the body and the punch that can cause the handle to be released from the body. Thus, the precedence relation for L_4 is $\{L_1, L_2, L_3$ *or* $L_5, L_6, L_7 \rightarrow L_4\}$.

It can be assumed that the punch is symmetrical in shape. The pivot fastens the handle, the body and the spring intersecting their lines of symmetry, and likewise the punch driver secures the handle, the body and the punch crossing their lines of symmetry. Consequently, the pivot and the punch driver must be completely withdrawn from the components they fasten in order to release the contacts between these components.

- ***L_5* (Handle-Punch Driver):**

No prerequisite action needs to be taken.

- ***L_6* (Punch Driver-Body):**

As the body is located next to the handle, to release the punch driver from the body, its contact with the handle must be undone beforehand. Thus, the precedence relation is $\{L_5 \rightarrow L_6\}$.

- ***L_7* (Punch Driver-Punch):**

To remove the punch driver from the punch, it must be previously withdrawn from the handle and the body. Thus, the precedence relation is $\{L_5, L_6 \rightarrow L_7\}$.

- ***L_8* (Handle- Spring):**

To remove the handle from the spring, it must be completely released from the body beforehand. Here, to ensure the complete removal of this part, the pivot and the punch driver should also be fully taken out. Hence, the precedence sequence for L_8 is {[L_1, L_2, L_3 (remove the pivot)]}, L_4, [L_5, L_6, L_7 (remove the punch driver)] → L_8}

- ***L_9* (Spring-Body):**

If the handle remains attached to the body, it blocks the access to the spring. Therefore, to establish this liaison, the handle should be disassembled from both the body and the spring. Besides, to ensure complete disassembly of this component, the pivot and the punch driver should also be previously removed. Hence, the precedence relation for L_9 is {(L_1, L_2, L_3), L_4, (L_5, L_6, L_7), L_8 → L_9}.

- ***L_{10}* (Punch-Base):**

The punch cannot be withdrawn from the base if the punch driver still remains in the assembly. This is because the complete removal of the punch driver allows the handle to have some motions, which may be a rotation around the pivot, given that the pivot still exists in the assembly. Thus, lifting the handle in an upward direction can give sufficient space for withdrawing the punch from the base. Thus, the precedence relation for L_{10} is {L_5, L_6, L_7 → L_{10}}.

- ***L_{11}* (Body-Base):**

The handle blocks the access to the body and the base. Thus, the handle has to be removed prior to establishing this liaison. Then again, the pivot and the punch driver must also be removed to guarantee the total removal of the handle. The body and the base are firmly secured with an intangible fastening agent. This type of fastening agent is defined as a fastener that has no physical presence within a product and that has no recovery value after disassembly, yet driving up disassembly cost, for instance, a press fit between two parts (O'Shea, 1999). Therefore, a disassembly tool is required to loosen their contact between the parts. In order to ease this operation, any parts that remain attached to them should be removed beforehand. This includes the punch and the spring. In addition, the cover should also be taken out since it blocks an access of the tool to the body. Hence, the precedence relation for L_{11} is {[L_1, L_2, L_3 (remove the pivot)], L_4, [L_5, L_6, L_7 (remove the punch driver)], [L_8, L_9 (remove the spring)], L_{10}, L_{12} → L_{11}}.

- ***L_{12}* (Cover-Body):**

No prerequisite action is required.

As a result, the precedence rules obtained from the answers to the questions on each liaison are rewritten in tabular form as shown in Table 2.

Liaison No.	Prerequisite Liaison
1	
2	1
3	1,2
4	1,2,3 | 5,6,7
5	
6	5
7	5,6
8	1,2,3,4,5,6,7
9	1,2,3,4,5,6,7,8
10	5,6,7
11	1,2,3,4,5,6,7,8,9,10,12
12	

Table 2. Summary of liaisons and their precedence.

Once the precedence rules are available, a graphical representation of all disassembly sequences can be generated. The diagram in Figure 5 contains all possible disassembly sequences, shown as a network of nodes and lines that illustrate the disassembly states and moves respectively. Each node contains sub-units, termed as cells, each of which refers to an established liaison, i.e. a disassembly operation. Within the node, cells are arranged in columns and rows, the number of which is equal to the number of liaison, in this case 1 to 12. Lines are drawn from the parent nodes to the child nodes to represent their precedent and subsequent operations. The unpainted cells refer to the disassembled liaisons, whereas the painted cells refer to the liaisons that are not yet established. The top of the diagram represents the fully assembled state, with all cells painted, whereas the bottom of the diagram represents the fully disassembled state. As the diagram progresses from one level to the next, liaisons are established to represent the elimination of components and thus the corresponding cells become unpainted.

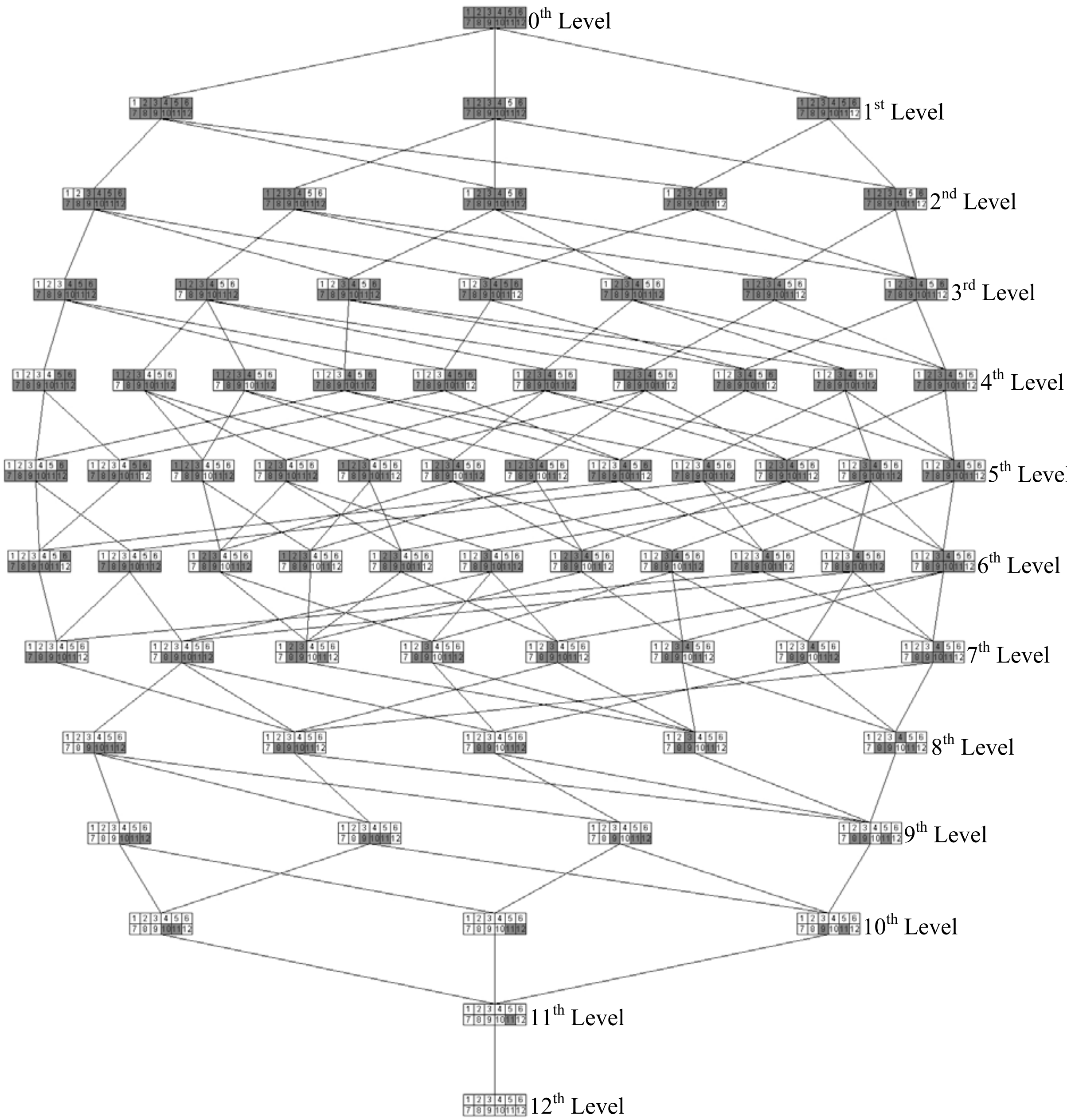

Figure 5. All possible disassembly sequences for the one-hole punch.

The disassembly starts with the initial node at the 0^{th} level of the diagram, containing the 12 liaisons of the hole punch. After that, the liaisons that require no prerequisite action are established at the 1^{st} level. These are, according to the precedence relations, the liaisons L_1, L_5 and L_{12}. From the second level onwards, any liaisons that are not yet established but have all their prerequisite fulfilled can enter the next level. For example, as L_1 and L_5 have been entered to the 1^{st} level, L_2 and L_6 can be established in the 2^{nd} level. In addition to this, the unions of any pairs that are formed between $\{L_1\}$, $\{L_5\}$ and $\{L_{12}\}$ produce another three disassembly states for the 2^{nd} level. The lines can then be drawn from the parent nodes to the child nodes to illustrate the disassembly transition. By progressively applying the procedure of liaison sequence analysis, all possible disassembly sequences can be generated as shown in Figure 5.

Selecting a Good Disassembly Sequence:

The next step in the procedure is to choose the best assembly sequence(s) by carrying out a winnowing process. This is done by progressively applying different constraints until all unfeasible disassembly sequences are eliminated. The first step in the winnowing process is to apply the concept of selective disassembly to explore an optimum disassembly path that leads to the removal of a selected part with reuse/remanufacture potential. As for the one-hole punch, the selected parts are the punch (part F) and the spring (part D) as shown in Table 1. The approach to selective disassembly starts with searching for any liaisons in the "liaison diagram" that are associated with these parts. According to the liaison diagram in Figure 5, the punch has connections with the punch driver (L_7) and the base (L_{10}), whereas the spring forms the links with the pivot (L_3), the handle (L_8) and the body (L_9). The next task is to find the shortest disassembly path that leads to the disassembly of all liaisons of the selected parts.

- ***Removing the Punch:***

L_7 and L_{10} appear in the disassembly sequence diagram for the first time at the 3rd and 4th level respectively, as shown in Figure 5. Therefore the punch can then be released for the first time at the 4th level. Since L_{10} appears at this level as the final operation, the search then moves backwards to the parent nodes at the higher levels to identify the possible disassembly sequences. The backward search has the advantage that usually less optional paths are available and less decisions have to be made. In this case there is only one parent node at each of levels 3, 2, and 1, which gives the best sequence of disassembling the punch, i.e. {L_5-L_6-L_7-L_{10}} as shown in Figure 6.

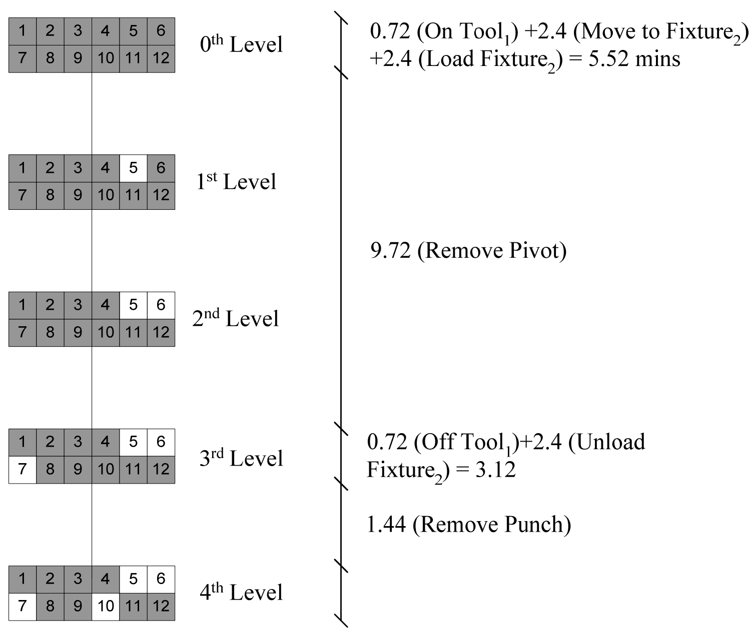

Figure 6. Final disassembly sequence and time mapping for the punch.

In addition, quantitative data, such as disassembly times, can be used to support the sequence selection. In the case of the punch this is not needed since there is only one option for the best sequence. However, disassembly times will be used later and therefore they are introduced here as additional evaluation criterion. The values of disassembly times in seconds are shown in table 3 and 4.

Fixture/Tool	Task Requirement	Time
Fixture 1	Move to, Load, Unload Fixture	1.44
Fixture 2	Move to, Load, Unload Fixture	7.2
Fixture 3	Move to, Load, Unload Fixture	3.6
Tool 1	Tool Actuation (on/off)	1.44

Table 3. Tool fetching time [O'Shea et al., 2000].

Code	Part	Fixture Requirement	Tool Requirement	Task Requirement	Time
A	Pivot (#7)	2	1	Use Tool, Grasp and Remove Part	9.72
B	Handle (#3)	-	-	Grasp and Remove Part	1.44
C	Body (#1)	3	-	Grasp and Remove Part	1.44
D	Spring (#8)	-	-	Grasp and Remove Part	1.44
E	Punch Driver (#6)	2	1	Use Tool, Grasp and Remove Part	9.72
F	Punch (#5)	-	-	Grasp and Remove Part	1.44
G	Base (#8)	3	-	Grasp and Remove Part	1.44
H	Cover (#4)	1	-	Grasp and Remove Part	1.44
-	Body_Cover_Int	1	-	Remove Fastening Agent	0.72
-	Body_Base_Int	3	-	Use Tool, Remove Fastening Agent	8.6

Table 4. The fixture, tool, and task requirements [O'Shea et al., 2000].

For removing the punch driver, Fixture 2 and Tool 1 are to be used. Therefore, the total time spent on switching on Tool 1, moving the one-hole punch to Fixture 2 and loading Fixture 2 is 5.52 sec., which is mapped to the transition from the initial state to L_5 as shown in Figure 6. The total time spent on withdrawing the punch driver plus the time for switching off Tool 1, 10.44 sec., is then mapped to L_5-L_6-L_7. Now that the Fixture 2 is no longer needed, it takes 2.4 sec. to unload it. This figure is mapped to the transition from L_7-L_{10}. Finally, the time required for removal of the punch is 1.44 sec. As a result, the total time required for disassembling the punch is 19.8 sec. The result of this winnowing process from the 0^{th} to the 3^{rd} level produces the best disassembly sequence for removal of the punch, which is {L_5-L_6-L_7-L_{10}}. In this case, using the first winnowing criteria of selective disassembly was sufficient to find the most feasible disassembly sequence without using additional criteria.

- ***Removing the Spring***

By using the same procedure explained in the previous section, the nodes that contain liaisons L_3, L_8 and L_9 appear in the liaison diagram at the 3^{rd}, 8^{th} and 9^{th} level respectively. Since L_9 appears at the highest level, all disassembly sequences that lead to this node are then investigated. Every line that enters this node is traced back in order to find all its parent nodes located in the next upper level. There is only one parent node found at the 8^{th} level, which is the establishment of L_8. Similar searches of parent-child node relations are performed until all the nodes that lead to the removal of L_3, L_8 and L_9 are established. The remaining nodes and branches that do not lead to these liaisons are removed from the sequence diagram. Thus, all possible disassembly sequences that lead to the removal the spring are generated as shown in Figure 7.

The next step in the winnowing process is to apply further constraints in terms of rules that specify which liaison or liaisons should be followed immediately by other liaisons in order to comply with common engineering sense. For instance, the pivot is connected to three other parts (L_1, L_2, L_3). There is no reason why the pivot should only be partially removed to release only L_1 or L_2 or L_3, where at the same time the full removal of the pivot would release al three liaisons in one single operation. Therefore it is only logical to assume that L_1, L_2, L_3 will be completed in direct subsequent order. The same applies to the punch driver in terms of L_5, L_6 and L_7. Therefore, two additional disassembly rules can be formulated by stating that L_1 should be followed immediately by L_2, immediately followed by L_3 ($L_1 \rightarrow L_2 \rightarrow L_3$), and also $L_5 \rightarrow L_6 \rightarrow L_7$.

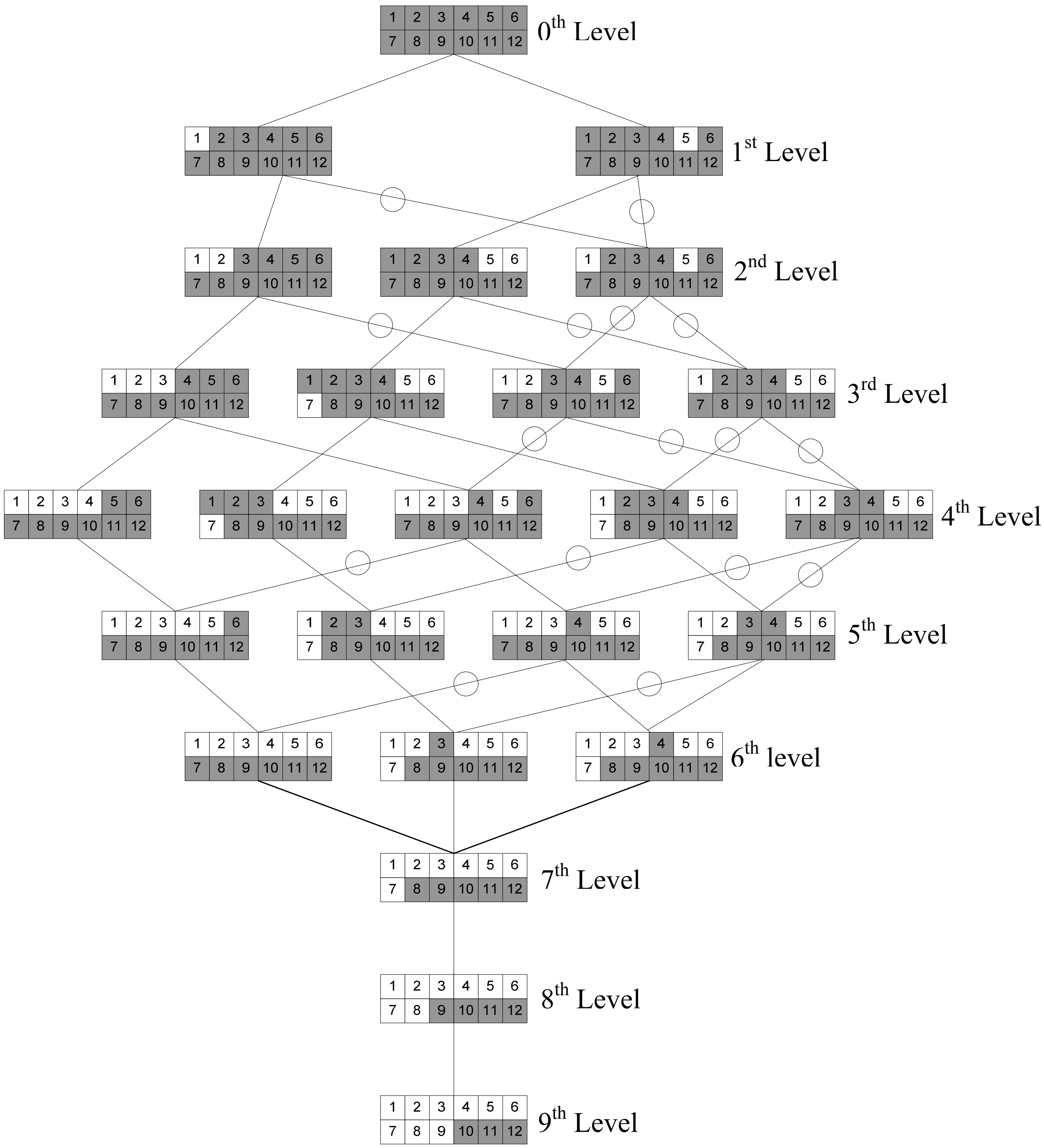

Figure 7. All possible disassembly paths that lead to the removal of the spring.

By applying these rules, the candidate nodes and lines that do not comply are identified for removal and marked with circles in Figure 7. Note that if all lines either entering or leaving a node are removed, the node can be deleted. As a result, there are 4 possible sequences remaining as shown in Figure 8.

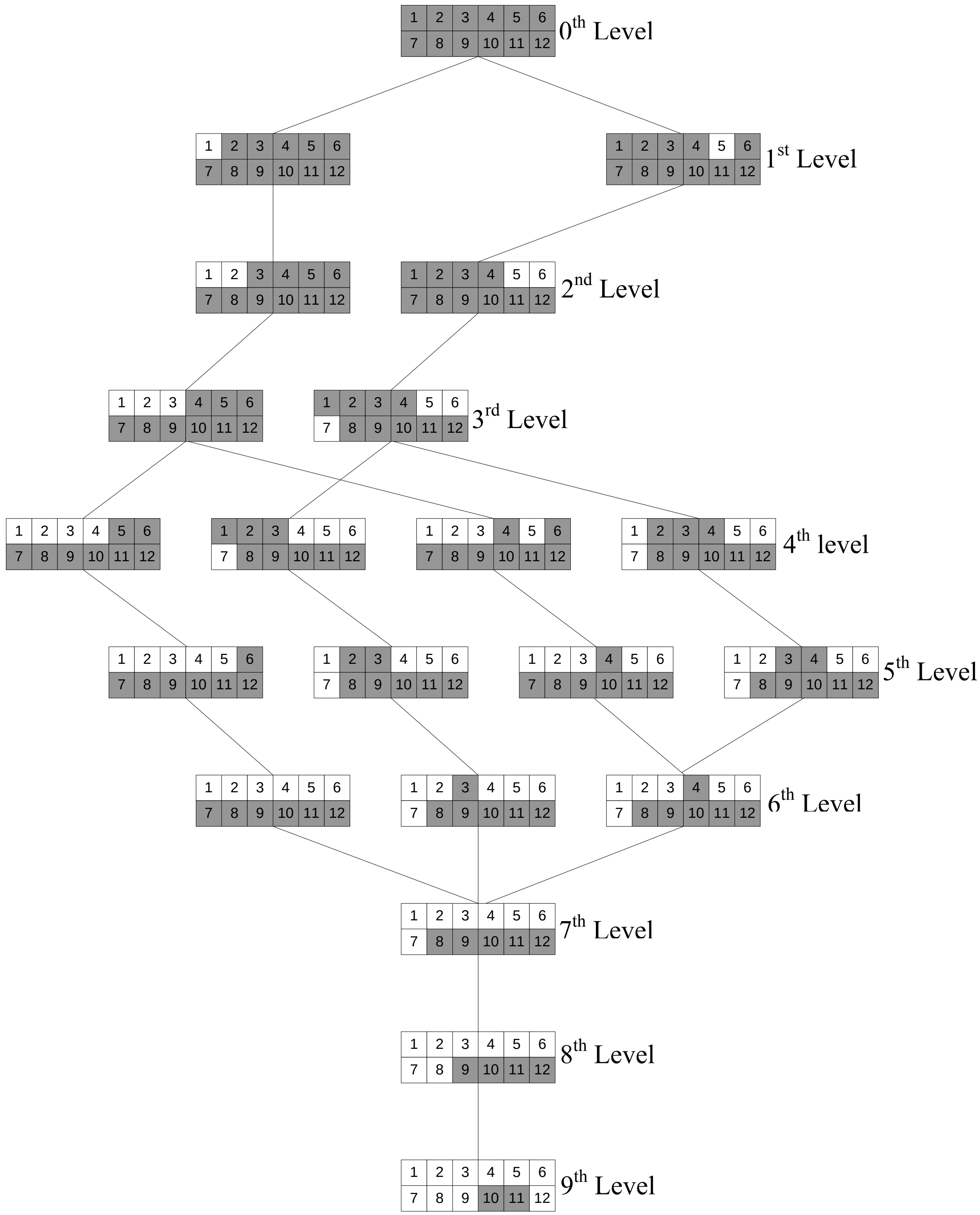

Figure 8. The remaining possible disassembly sequences after applying the constraints.

In order to further reduce these sequences, the quantitative data in the form of disassembly time (Table 3 and 4) is to be used. Time spent on any set of tasks that is performed to remove a component is termed as the value added time, later mapped to the disassembly state. On the contrary, time spent on any group of tasks that is done to fetch a tool or a fixture is termed as the non-value added time, and later mapped to the disassembly transitions.

There are four disassembly sequences remaining in the diagram: {L_1-L_2-L_3-L_4-L_5-L_6-L_7-L_8-L_9}, {L_1-L_2-L_3-L_5-L_6-L_7-L_4-L_8-L_9}, {L_5-L_6-L_7-L_4-L_1-L_2-L_3-L_8-L_9}, and {L_5-L_6-L_7 -L_1-L_2-L_3-L_4-L_8-L_9}.

Mapping the quantitative data to {L_1-L_2-L_3-L_4-L_5-L_6-L_7-L_8-L_9}:

In removing the pivot, Fixture 2 and Tool 1 are both required. Therefore, the sum of the non-value added time is 0.72+2.4+2.4, referring to the time spent for switching on Tool 1, moving product to Fixture 2, and loading Fixture 2 respectively. These time values are mapped to the transition state from the pre-disassembled state to L_1. The total time spent on removing the pivot including the time spent for switching off the tool, 10.44 sec., is then mapped to the transition from the pre-disassembled state to L_1, L_2, and L_3, hence resulting in the complete removal of these components. At this stage, the fixture is still loaded since it is used for removing the punch driver. After L_1, L_2, and L_3 have been completed, L_4 is automatically released. Hence, there is no real task performed in establishing this liaison. Prior to removing the punch driver, Tool 1 is to be used again. Time required for switching on Tool 1, 0.72 min, is mapped to the transition from L_4 to L_5. The time spent on withdrawing the punch driver plus the time spent for switching off Tool 1, 10.44 sec., is mapped to L_5, L_6, L_7 resulting in the complete removal of these components. Now that the Fixture 2 is no longer required, time spent on unloading it, 2.4 sec., is mapped to the transitions L_7, L_8. It takes 1.44 sec. to carry out L_8, referring to the removal of the handle from the spring. Time spent for removing the spring, 1.44 sec., is finally mapped to the terminal node. The total time spent on carrying out this disassembly sequence is 32.4 sec. as shown in Figure 9.

Mapping the quantitative data to: {L_1-L_2-L_3 -L_5-L_6-L_7-L_4-L_8-L_9}:

This disassembly sequence entails a similar order of component removal as the previous sequence. The pivot is firstly removed, followed by the punch driver, the handle and finally the spring. Thus, the total time spent on this disassembly sequence is 32.4 sec, which is same as previous sequence as shown in Figure 9.

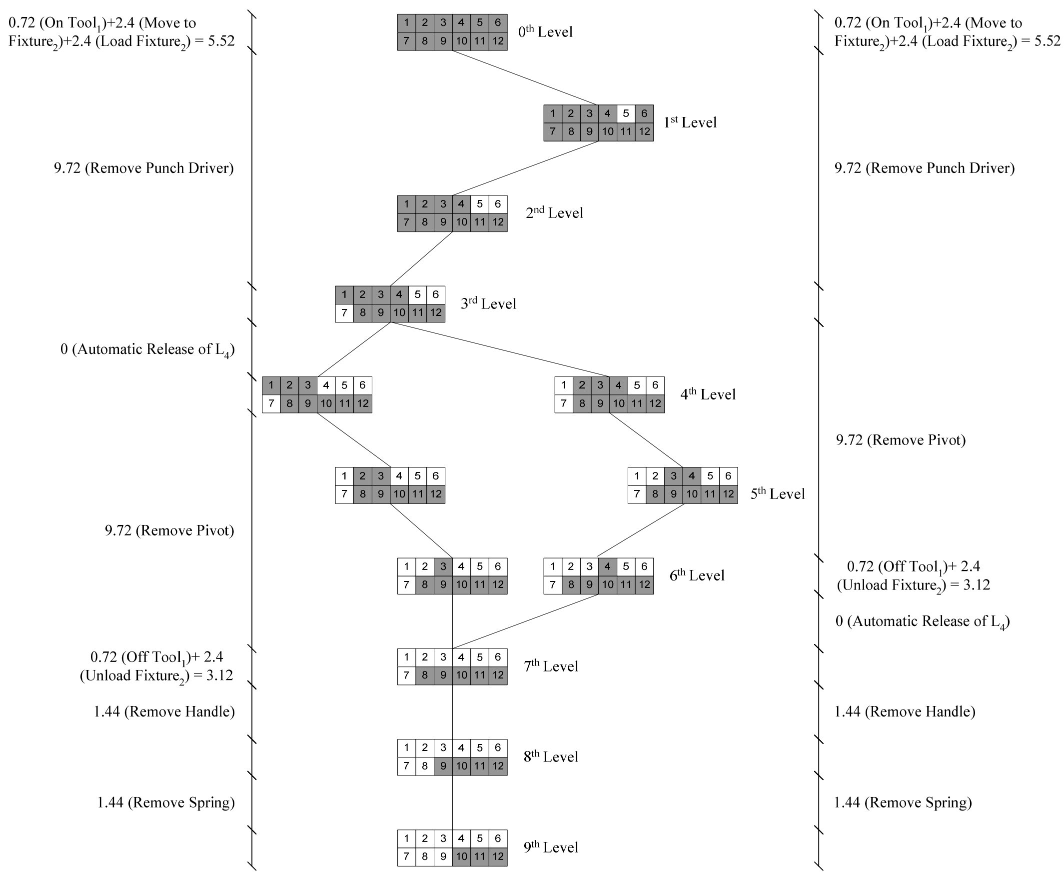

Figure 9. Time mapping of sequences {L_1-L_2-L_3-L_4-L_5-L_6-L_7-L_8-L_9} and {L_1-L_2-L_3-L_4-L_5-L_6-L_7-L_8-L_9}.

The mapping of the other two sequences {L_5-L_6-L_7-L_4-L_1-L_2-L_3-L_8-L_9} and {L_5-L_6-L_7-L_1-L_2-L_3- L_4-L_8-L_9} can be done in the same way, and is shown in Figure 10.

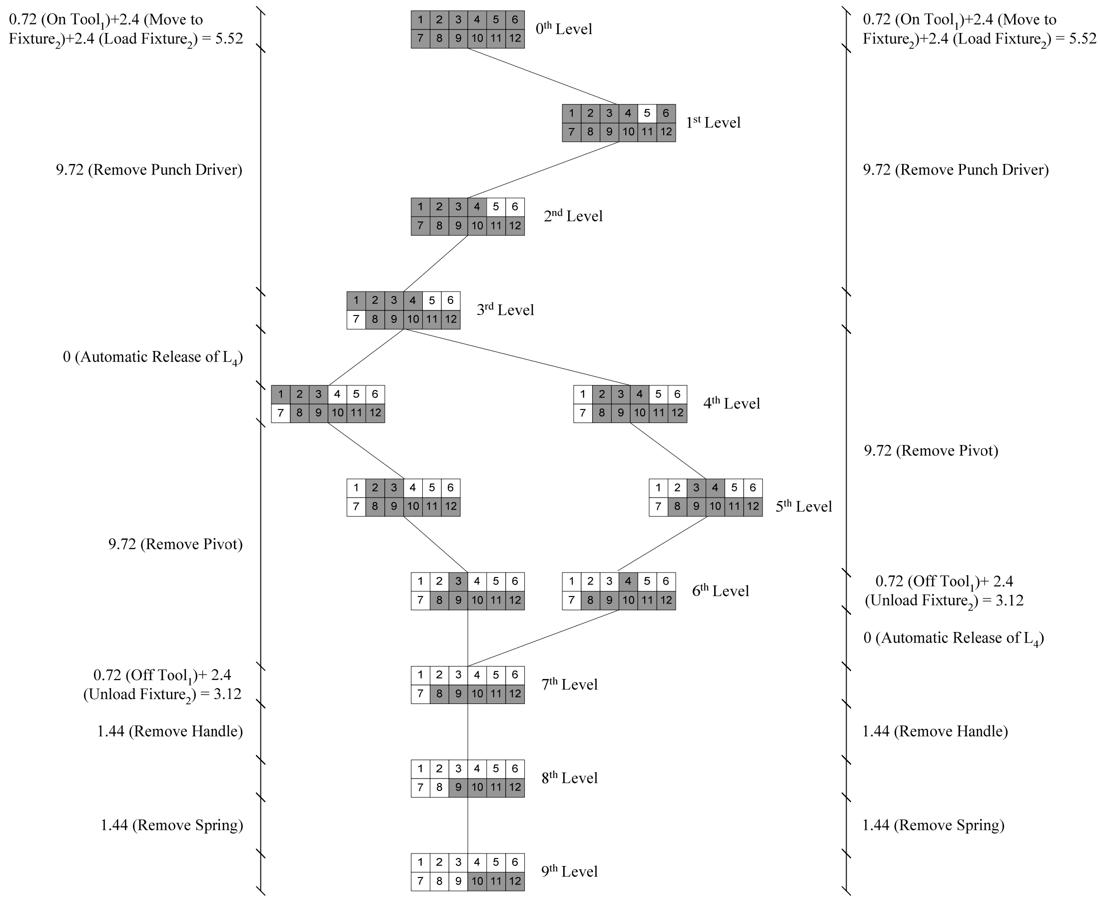

Figure 10. Time mapping of sequences {L_5-L_6-L_7-L_4-L_1-L_2-L_3-L_8-L_9} and {L_5-L_6-L_7- L_1-L_2-L_3- L_4-L_8-L_9}.

Although, these four sequences include different orders of component removal, they are still equal in terms of disassembly time. However, it can be assumed that the two selected parts, punch and spring, are disassembled during the same disassembly operation. As the disassembly sequence progresses from the 0^{th} level to the 3^{rd} level, L_5, L_6 and L_7 are the first three liaisons that need to be carried out to remove the punch. As both the {L_5-L_6-L_7-L_4-L_1-L_2-L_3-L_8-L_9} and {L_5-L_6-L_7-L_1-L_2-L_3-L_4-L_8-L_9} for the spring encompass the same first three liaisons as the liaison sequence for the punch {L_5-L_6-L_7-L_{10}}, either of them should be implemented as a feasible disassembly sequence for removing the spring since they lead to the early removal of the punch. Finally, instead of following the original sequences, L_{10} should be carried out right after L_5-L_6-L_7 in order remove the punch, followed by the rest of the sequences.

CONCLUSIONS

The methodology for selective disassembly sequencing proposed in this paper was derived by Nevins and Whitney (1989) for assembly. The differences of the application for disassembly have been demonstrated, and the case study of the one-hole punch was used to prove that the methodology is applicable to disassembly processes. It can be found that the winnowing process for disassembly is much easier then for assembly because of the selective disassembly approach, which automatically provides a significant constraint on possible sequences. Although the additional criterion of disassembly times was used in the case study, it may not be necessary to apply this type of quantitative data which is often difficult to find. The time consuming tasks in this methodology, such as the generation of the sequence diagram and the deletion of sequences in the winnowing process, can easily be carried out with the help of a computer software, which was developed for this purpose.

FUTURE RESEARCH

Some of the issues that need to be tackled as a future research are the creation of liaisons between the components and associated precedence relations between them. This could be addressed by extracting the liaison relations from CAD drawings of the original product. Later, this information could be used to create the required precedence relations for selective disassembly. The other issue is the tediousness of the winnowing process once the product under investigation becomes complex. The authors of this paper are developing an expert system to speed up this process.

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