

# Concepts and verification model for pressure triggered one-to-many disassembly fasteners

Barbara Willems, Wim Dewulf, Joost R. Dufflou  
Katholieke Universiteit Leuven, Mechanical Engineering Department, Belgium

## Abstract

It is explained how 'one-to-many' fasteners can contribute to achieve cost-efficient disassembly. These fasteners use advanced materials or structures as a catalyst for disassembly, allowing multiple assemblies to separate simultaneously after exposure to specific, external triggering conditions. In this paper the emerging techniques in this area are sketched and evaluated, according to their generic applicability and the degree of imbedded automation of the triggerable disassembly activity. In the remainder of this paper, a systematic development strategy for structure-based *one-to-many* disassembly concepts is presented using topology optimisation. Illustrated with pressure-based fastener configurations, examples are given of how *one-to-many* fasteners could look like and how they can be implemented in products.

## Keywords

Active disassembly, One-to-many disassembly, Fastener development

## 1 INTRODUCTION

From an economic point of view the productivity associated with commonly available disassembly methods today seldom makes disassembly the preferred end-of-life solution for massive take back product streams. In consequence systematic reuse of parts or components, or recycling of pure material fractions are normally not achievable. Economic models demonstrate that the efficiency of disassembly operations should be increased an order of magnitude to assure the competitiveness of ecologically preferred, disassembly oriented end-of-life scenarios [1]. Traditional disassembly processes are no alternative for shredding, due to their time-consuming *one-to-one* nature: *one* unfastening action can unlock only *one* fastener [1]. To promote disassembly, the disassembly time of each joint should be drastically decreased with 70 to 80%. It was shown that the fully automated disassembly techniques do not allow to overcome this efficiency gap if not combined with innovative reversible joints such as *one-to-many* fasteners. By using an external trigger such as heat, pressure, radiation, etc. [2] combined with an appropriate choice of the material or structure of the joint, great potential is created for lowering disassembly time and cost since *each trigger signal* can disassemble *multiple* assemblies equipped with *one-to-many* fasteners simultaneously.

## 2 ONE-TO-MANY DISASSEMBLY

### 2.1 Literature review

An early attempt to enhance disassemblability can be found in Masui *et al.* [3], who introduced the idea of embedding a nickel-chrome wire inside the joint between the mutually recycling-incompatible funnel and screen of a CRT during manufacturing. Applying an electric current through the wire causes a distributed Joule effect, which induces thermal stresses, hence causes separation by fracture along the joint. Klett *et al.* [4] applied the same working principle in a generic fastener by integrating a heating wire in a plastic section of a bolt. In this case, the heat, generated by the resistance wire, causes melting of the plastic. Another generic fastener developed by Klett *et al.* [4] is a complex nut and bolt configuration based on a set of balls that block the relative movement between

parts. Applying a magnetic field creates free space for the balls, hence allowing a disassembly of the bolt configuration. Nishiwaki *et al.* [5] and Li *et al.* [6] proposed the use of specifically designed snap-fits, which exhibit a non-homogeneous thermal expansion, hence structural deformation when subjected to a well-localised heat supply. This deformation suffices to unlock the snap connection. Some additional concepts were recently suggested by Braunschweig [7], but have only reached the level of a rudimentary sketch in a prospective paper. These concepts share the aim of enhancing the disassemblability of products. Moreover, in some cases, they lead to innovative solutions that can solve very complex disassembly problems, as shown in the separation of the CRT monitor glass fractions. However, they also share the drawback that only a limited number of fasteners can be unlocked simultaneously. Moreover, they require a very localised application of the trigger signal.

A second set of contributions can be considered as truly active disassembly concepts. By means of innovative materials or structures, a set of connections is created for which an external trigger initiates the unfastening process. The concepts are developed such that they are applicable as modular connections in a wide range of products and an unlimited number of connections can be unfastened with the same disassembly action, without requiring internal links, as long as the joints are positioned in the influence field of the trigger signal. The most mature research on active fasteners yet is based on shape memory materials (SMM). SMM components are able to return to an initially 'trained' shape when heated above a trigger temperature. Chiodo *et al.* [8,9] designed snap-fits made of shape memory polymers (SMP). When the product is heated, all snap fits are deformed thus releasing the individual components. Sakai *et al.* [10] investigated similar concepts making use of the shape memory effect and made prototypes of SMM joints of a flat screen monitor. Jones *et al.* [11] describe the use of shape memory alloys (SMA) as 'muscle wires', connected to e.g. snap-fit fasteners. After triggering at the end of life phase, the wire contracts in such a way that the snap-fit is unfastened. Sakai [10] describes the use of SMA screws. The screws have a separate head that is fixed on the threaded shaft by means of a tight fit. When heat is

added, the SMA head changes its shape thus releasing the shaft. Chiodo *et al.* developed a similar concept with SMP [9]. The industrial applicability of these concepts remains yet very low due to unsatisfactory performance on three properties essential for industrial use and valorisation: long-term stability, shock resistance and transition temperature interval.

Next to the SMM based concepts, only two authors provide concepts that could be categorised under the term *one-to-many* disassembly. Suga [12] used a chemical reaction as trigger for disassembly actions. A hydrogen storage alloy was presented as a bonding intermediate, which is pulverized when it absorbs hydrogen. Neubert [13] proposed three other working principles, which make use of respectively the expansion of water when freezing, the soluble characteristic of materials and pneumatic expansion.

Initial investigations of the above described concepts have identified that the solutions proposed in literature only form a starting point for a much wider gamut of concepts that wait to be investigated, taking into account the wide range of triggers, materials and configurations. These three parameters are yet not fully explored, though they are indispensable when developing one-to-many fasteners. They will be briefly outlined in Section 2.2.

## 2.2 One-to-many fasteners

### Triggers

As described above, the selection of a specific external trigger, such as heat, pressure, etc., is essential for the success of a concept. To avoid undesired interaction between the trigger and the product, comprising one-to-many fasteners, the use environment of the product should be scanned to define the utility range of each available trigger. A particular aspect of the potential undesired interaction between the external triggering process on the one hand, and the product on the other hand, is the unforeseen occurrence of the trigger signal during the functional lifetime, giving rise to functional breakdown or even safety problems. This is one of the impediments for realising suitable one-to-many fasteners.

In reaction to this problem, attempts are typically made to raise the trigger level needed to activate disassembly to extreme values. These however reduce the economic and

environmental benefit achievable by the active fastener paradigm. Another strategy can be to develop hybrid concepts that are characterised by the imperative presence of two simultaneous trigger signals, with negligible chance of appearing simultaneously during the regular use period of the product, in order to activate the disassembly process. However, no references have been found that investigate the latter strategy.

As described in Section 2.1 various triggering concepts are suggested in literature. Figure 1 summarises these concepts, structured according to the dominant physical variable the trigger affects, e.g. temperature, force, pressure, etc. In addition, this list is completed with other potential trigger mechanisms to be used for *one-to-many* disassembly. For each physical variable a classification is made according to the trigger principle. Since the activation of the fastener will only take place if the value of the physical variable varies within a certain time span, this has to be included in the trigger description, e.g. heating representing a temperature increase, etc. In the third column, a set of mechanisms is described that can be used to realise the trigger in an effective application. Finally, the corresponding global effects of implementing the trigger concept, causing disassembly, are listed in the fourth column.

### Material

In combination with the trigger system, the selection of the material is of particular importance to guarantee a desired reaction to an external triggering signal. On the one hand, specific, well-designed materials can be used that are conditioned to perform as required. In many cases this implies exotic materials or material combinations with a strong non-linear behaviour under trigger conditions, e.g. the hydrogen storage alloys (Al-LaNiAl alloy) or the shape memory alloys (Ni-Ti alloy). These alloys are expensive and mostly incompatible with other materials applied in the product, causing obvious problems for sorting and recycling during End-of-Life (EOL) treatment. When using well-designed materials, the configuration only fulfils a secondary role. The material is responsible for the desired performance of the fastener, where the configuration adopts standard shapes such as the traditional cantilever beam for snap fits.

Physical variable	Trigger	Mechanism	Possible global effect when trigger is applied
Temperature °C	Heating	Radiation Convection Conduction	Deformation, Expansion, Melting, Evaporation, Sublimation, Pyrolysis, Creep, Thermal Stress, Inverse material expansion, etc.
	Cooling	Radiation Convection Conduction	Brittleness, Shrinking, Inverse material expansion, etc.
	Electric Current	Joule Effect	Deformation, Expansion, Melting, Pyrolysis, Creep, Thermal Stress, Inverse material expansion, etc.
Force N	Direct Force	Pushing force Rotation	Elastic Deformation, Plastic deformation, Splintering, Breakage, Pulverisation, Creep, Function failure, etc.
	Acceleration	Rotation Axial acceleration	
	Electric Charge	Attraction/Repulsion	
	Magnetism	Attraction/Repulsion	
Pressure Bar	Ambient pressure change	Equalize pressure between ambient and housing with internal lower pressure Change pressure between ambient and closed gas-filled cavity	Function Failure
Mechanical waves Hz	Mechanical Vibrations	Exposure to eigenfrequencies Exposure to high amplitude frequencies	Splintering, Breakage, Pulverisation, Function Failure, etc.
	Sound Waves	Exposure to eigenfrequencies Exposure to high amplitude frequencies	
Electromagnetic Waves Hz	Adding of microwaves	Microwave source triggers material Microwave source triggers catalysts	Splintering, Breakage Expanding, Melting, Evaporation, Sublimation, Reduction of stiffness, Thermal stress, etc.
	Addition of UV-light	Radiation: UV-lighting systems	Corrosion, Brittleness, Reduction of Stiffness, etc.
Chemics 0-100%	Ambient humidity change	Sprinkling with water Submerging in water Steam	Shrinking, Expanding, Dissolving, Reduction of stiffness, Corrosion, etc.
	Adding of reagents	Submerging in reagent Sprinkling of product with reagent	Dissolving, Reduction of Stiffness, Corrosion, Brittleness, etc.
	Adding of enzymes	Influence of enzymes on product	Bioerosion, Dissolving, Reduction of Stiffness, Corrosion, Brittleness, etc.

Figure 1. Overview of possible trigger mechanism for active disassembly

On the other hand, regular engineering materials can be used. In this case, the configuration of the fastener will determine the reaction on the trigger signal. The advantage of the latter strategy is that the fasteners do not need to be sorted out before parts are sent to material recycling. This is of particular interest when integral fasteners are implemented, such as snap fits.

### Configurations

A third aspect that determines the success of one-to-many fasteners is the configuration design. Especially when common engineering materials are used, this topic requires substantial attention. Since the reaction to the external trigger is not mainly determined by the material but by the structure, careful engineering of the fastener can influence the performance of the fastening concept drastically. This aspect will be illustrated in Section 6 of this paper.

### One-to-many fastener development

When developing new one-to-many fasteners, these three aspects should be considered. In literature, material-based one-to-many fastener descriptions can be found, using common fastening configurations such as snap fits. In contrast, a systematic development strategy for configuration-based fasteners is lacking. In the remainder of this paper, the use of topology optimisation for designing one-to-many fasteners will be illustrated, assuming regular engineering materials are to be used.

## 2.3 Research scope

When evaluating the possible triggers outlined in Figure 1 and comparing these with the use environment of a range of standard Electric and Electronic products (E&E) [14], pressure seems to be the most stable variable of all proposed triggers. During regular use of E&E products, pressure levels vary between 0.2 bar, in cargo transport 12000m above the earth, and 2 bar, 10 m below sea level. This implies a comfortable potential trigger range between 4 and 100 bar. However, to reduce the dismantling energy the upper limit should preferably be reduced, e.g. to 20bar. The pressure-triggered fastener concepts are designed such that a change of ambient pressure originates a deformation of the fastener shape causing unlocking. This effect can be generated by a regular, empty, closed, box-shaped structure. However, to minimize the energy use to gain the desired reaction, the internal structure within the empty box can be used to generate a mechanism that stimulates and steers the deformation once the pressure change is applied.

The procedure to design pressure-based one-to-many fasteners is illustrated in the remainder of this paper. Section 3 will briefly discuss the used configuration design method, Section 4 illustrates the implementation opportunities and Section 5 verifies the design results with some finite element calculations.

## 3 CONFIGURATION DESIGN METHOD

The selected method to approach the stated problem is *topology optimisation*. This technique for optimising solid structures involves the determination of features such as the number, location and shape of holes and the connectivity of material within a design domain [10]. By defining the problem as a regular optimisation problem with an objective function and constraints, the optimal structure will be generated within a predefined domain.

For the selection of the design domain of the pressure-based fastener, inspiration was derived from regular snap fits since these have proven their usefulness during assembly processes [15] but lack the necessary fine-

tuning for disassembly. Combined with the need for a closed, gas-filled cavity, the initial starting domain as presented in Figure 2 was chosen. The domain is divided in small areas, called elements, of which the material content is subject of the optimisation process. This variable can fluctuate between 0, when no material is assigned to the element, and 1, when the element is completely filled. Each value in between represents a composite of material and voids, e.g. foam.

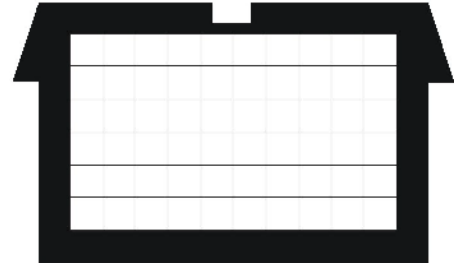


Figure 2. Initial starting domain for pressure-based one-to-many disassembly fastener

The objective function maximises the displacement of the upper two corners acting as snapping features, caused by the disassembly trigger, being pressure acting on the entire exterior boundary. This displacement should be sufficiently large to perform the unsnapping behaviour during disassembly. The displacements during assembly and use are constrained to guarantee the required snap fit properties. Since transitions between intermediate material compositions, e.g. foam and dense material, are difficult to produce by injection moulding, the variable will be forced to take binary values. Using topology optimisation an internal structure will be defined that guarantees this prescribed behaviour.

## 4 IMPLEMENTATION

### 4.1 Results

Figure 3 presents the 2D solution of the topology optimisation problem outlined above as obtained using Matlab. It is clear that to maximise the inward displacement of the two upper corners of a rectangular shape, the connecting upper beam should deflect, hence pulling the corners to each other. The applied pressure results in a distributed force over the top beam, which works in the desired direction to deflect it. The pressure forces on the sides will be transformed to a pulling force acting on the upper beam by the built-in mechanism; the internal structure rotates around the four hinges converting all horizontal forces to vertical ones. The working principle of the internal mechanism when a pressure force is applied is presented in Figure 4.

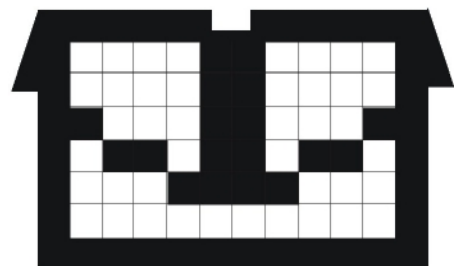


Figure 3. Solution of the topology optimisation problem to define the inner structure for pressure-based one-to-many disassembly fastener

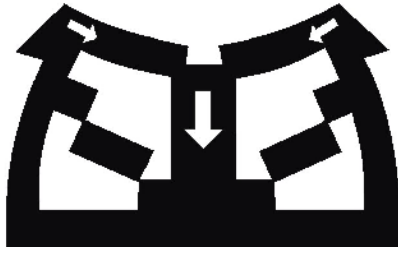


Figure 4. Reaction of the structure on the application of a pressure force on the exterior boundary of the domain

It is obvious that the level of detail for each solution depends on the roughness of the mesh. As presented in Figure 3, the hinges between the solid material parts are too fragile to be implemented in reality. Refining the mesh produces more detailed solutions but automatically increases the calculation time to reach an optimal solution. When using topology optimization, compromises need to be made between speed and detail. Regarding this dilemma it is important to bear in mind that all results still require an engineering step before implementation is possible. At that point problems concerning the minimal thickness of solid parts or the design of flexible hinges can still be solved.

Figure 5 presents the detailed solution generated with a 60x40 mesh instead of the 12x8 mesh in Figure 3.

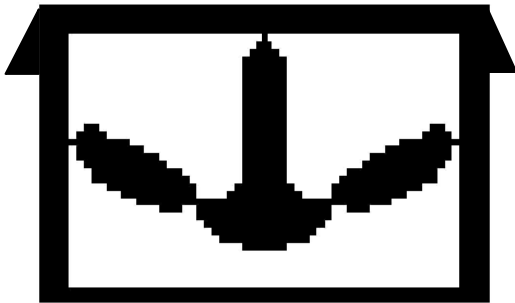


Figure 5. Refinement of the mesh

#### 4.2 Remarks

The 2D solution presented in Section 4.1 is merely an illustration of the used method. Due to the characteristics of pressure a 3D structure will be indispensable. However, this will not be covered in this paper.

Depending on the specific product structure or the design of parts that need to be connected, different solutions can be generated. The use of a snap-fit like structure or the symmetric position of snapping features is not compulsory. When reformulating the problem, e.g. as heat-triggered or vibration-triggered, one should clearly reformulate the objective function and constraints, but the engineering step to transform the results into producible fasteners remains similar.

### 5 VERIFICATION

#### 5.1 Finite element results

A finite element calculation was made to verify the results obtained from topology optimisation. Figure 6 presents both the commonly used snap fit and the newly designed one-to-many snap fit. In both designs, a horizontal displacement of the snapping feature larger than 1.5mm is required to guarantee a snap-fit behaviour. Regarding the total size of the design, this can be considered a large deformation; implying geometric non-linearity should be assumed.

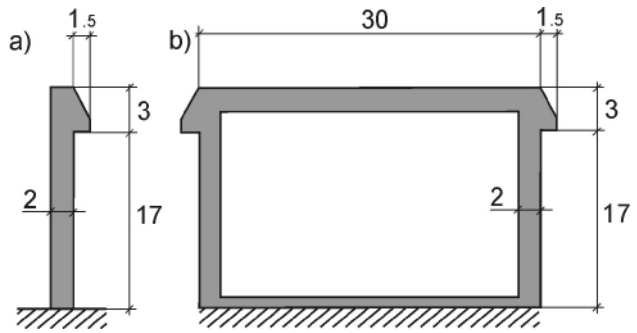


Figure 6. Dimensions (mm) of a) the regular snap fit, b) the initial pressure-based fastener

Figure 7 represents the deformed shape of the initial empty fastener when a pressure load of 70 bar is applied. The displacement of the snapping feature under these conditions is 0.8 mm in the opposite direction as desired. As stated above, when the applied pressure is sufficiently increased, the empty design will eventually shrink as well, performing the desired unsnapping behaviour. However, this would require very high pressures, which reduces the usability of this concept.

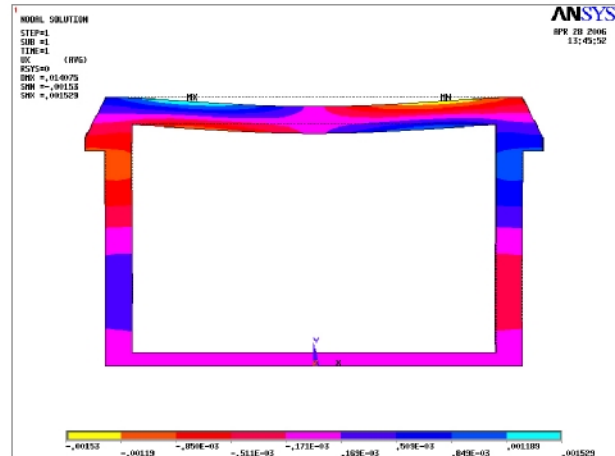


Figure 7. Deformed empty fastener under a pressure load of 70bar (colours represent horizontal displacements)

In contrast, the results presented in Figure 8 show a displacement of the snapping feature of 1.5mm under the same pressure load of 70bar.

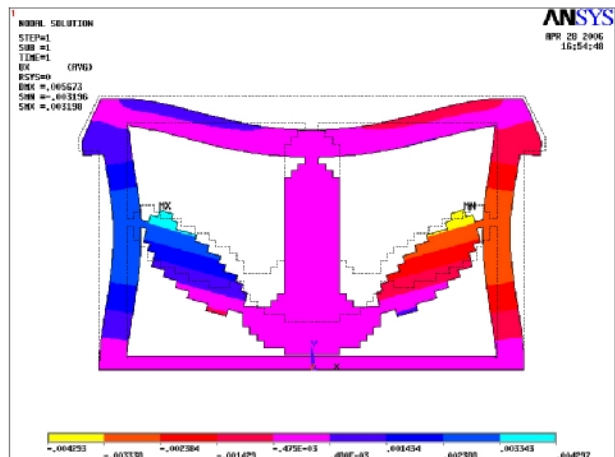


Figure 8. Deformed optimised fastener under a pressure load of 70bar (colours represent horizontal displacements)

## 5.2 Discussion

Test runs have shown that the selection of the initial design domain (Figure 6) has a strong impact on the deformation of the structure. Changing the width/height ratio can offer entirely different results. This characteristic can be used to design a desired reaction on trigger signals. The trigger signal of 70 bar used in the presented configuration can easily be modified by varying the initial domain.

## 6 ENGINEERING

As stated above, the results from topology optimisation runs still need to be translated into producible fasteners. Determination of the final layout, material selection and selection of the way to implement the fastener in the product as an integral feature or as a discrete part, are aspects still to be fine-tuned. In this regards the product target group of the specific fasteners should be considered.

The pressure-triggered fasteners as envisaged in this study are designed to be implemented in large household appliances from the E&E category. First, because Willems et al. [1] proved that for this category disassembly based EOL treatment becomes profitable once the disassembly time is reduced with 70%. Second, the development of these products is less driven by miniaturisation, which leaves sufficient free space to implement the relatively large pressure-based fasteners as designed in Section 4.

### 6.1 Final layout

Comparing the results of both configurations presented in Section 5, the use of the internal mechanism is responsible for a drastic efficiency increase. When evaluating the displacement values and graphs, it is clear that the upper beam is reducing the ability of the upper two snapping features to move inwards. To overcome this problem, the stiff connecting beam is replaced with a slightly bended one pointing inwards.

A second adjustment is the location of the horizontal beam. By moving it downwards, the displacement of the snapping feature is maximised on the lower edge of the hook (point a - Figure 9) instead of at the top of the snap fit (point b - Figure 9). The combination of both changes, results in an efficiency increase of 40%. A pressure of 70bar results in a snap fit displacement of 2.1 mm.

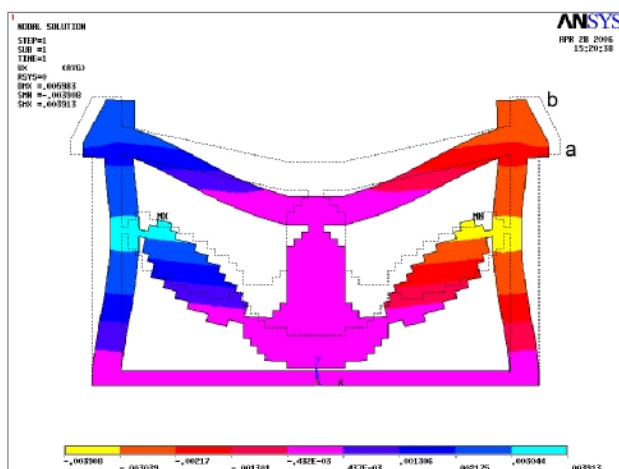


Figure 9. Final layout of the pressure-based snap fit under a pressure of 70bar (colours represent horizontal displacements)

### 6.2 Materials

When running the topology optimisation program the material properties of the part have to be clearly defined.

Multiple test runs with diverse polymers showed that the implementation of flexible hinges is required to obtain an amplification mechanism to increase the displacement of the upper corners acting as snapping features. Rotheiser [16] stated that the optimal material for flexible hinges is PP or in second place any other crystalline polymer. A second consideration to take into account is that the compatibility of materials from different parts should be guaranteed to eliminate dedicated sorting at EOL and to make joint material recycling feasible.

In E&E the overall use of PP is about 12% compared to 14% for ABS and 28% for PS. These categories are the most dominant ones, summing up to 54% of the total plastics consumption for E&E. However, when focussing on the large domestic household appliances, which determine the target group of the proposed fasteners, the use of PP is considerably reduced to a negligible fraction. The material use is dominated by ABS/PC blends [17].

The conflict between the optimal material for the product housing, ABS/PC blend, and for the one-to-many fasteners, PP, requires a compromise. As specified in plastics recycling compatibility matrices, both materials cannot be mixed for material recycling [18]. On the other hand, ABS-based blends are from the amorphous plastics group, which is a material category unsuitable for the fabrication of flexible hinges. Moreover, the properties of PP do not fit the required specifications needed for large domestic household products.

Only the design of a discrete fastener that is easy to remove from the product housing, can offer a solution to reconcile the conflicting requirements.

### 6.3 Implementation

Figure 10 presents a possible configuration for integration of pressure-based fasteners in an assembly. To overcome the material incompatibilities between the product housing and the fastener, the configuration is set-up such that, once pressure is applied, both snap fits will unlock.

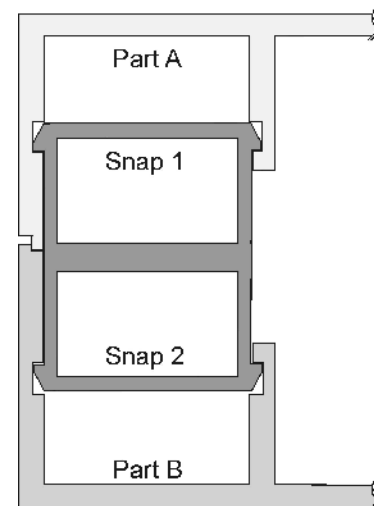


Figure 10. Implementation details

The combination of two snap fits into one part can as well be used to include selective triggering. If snap fit 1 is triggered at 50 bar where snap fit 2 will only unlock the connection at 80bar, stepwise disassembly becomes feasible.

## 7 SUMMARY AND FUTURE RESEARCH

Topology optimisation is a promising technique for developing configuration driven one-to-many disassembly techniques. This paper summarizes a systematic development methodology, illustrated with the example of

a pressure-based fastener. The topology optimisation problem was briefly explained without elaborating on the mathematical problem solving techniques, though the problem definition in combination with some output graphs were presented to illustrate the solution. Result verification proved that well-optimised structures can be obtained, applicable in real product configurations.

Future research will focus on the elaboration of the current pressure concept. Changing the initial design domain will result in a variety of design solutions to be used in a series of different product configurations. This methodology will be expanded to other triggering concepts for configuration driven *one-to-many* disassembly concepts, such as vibration-triggered fasteners and fasteners triggered with centrifugal force. The extension to three-dimensional solutions will be indispensable for all concepts. Finally, attention will be paid to the producibility of the generated structures. Steps will be undertaken to transform the initial concepts into production ready configurations.

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#### CONTACT

Barbara Willems

K.U.Leuven, Department of Mechanical Engineering, Celestijnenlaan 300A, B-3001 Leuven, Belgium, [Barbara.Willems@cib.kuleuven.be](mailto:Barbara.Willems@cib.kuleuven.be)