Circular Product Design Strategy Criteria & Guidelines

1. Attachment & Trust

Focus points	*Product design guidelines*
1. Attachment **a. Emotional value** **- *Narrative*** **b. Social value** **c. Personalization**	a. <u>Product has strong emotional value for its user</u> • *Product should facilitate the build-up of an emotional connection with its user* • Product should provide services, contain information, or convey meaning with emotional value or relevance • Product should reflect a *narrative:* a unique and shared personal history with its user; • When was it acquired by its user? • How? • From whom? • From where? • From what materials is the product made? • What unique service/information/ability does the product contain? b. <u>Product has strong social value for its user</u> • *Product should facilitate the build-up of social connections by the user* • Product should provide services, contain information or convey meaning that are relevant within the user's social environment • Product should be able to reflect and adapt to developments and trends within the user's social environment c. <u>Product can be personalized by its user throughout time</u> • *Product can be adjusted by its user to more appropriately reflect emotional and/or social values* • Product adjustments can take place throughout time of use • *Product can be adjusted by its user to more closely match user's preferences* • Product adjustments can take place throughout time of use
2. Detachment **a. Lack of emotional demand or expectation**	a. <u>Product has no emotional or social value to its user</u> • *Product should fail to facilitate emotional demand by its user* • Product should not provide services, contain information, or convey meaning that have limited or no emotional value or relevance to the user • *Product should fail to facilitate high expectations by its user* • Product should not provide services, contain information, or convey meaning that heighten user's expectations of product's performance
3. Design **a. Attractive, fashionable, personal** **b. Materials and surface**	a. <u>Product has an attractive and fashionable design</u> • *Product's design should personally appeal to its user* • User should have the opportunity to self-adjust or influence product's design to match personal preferences b. <u>Product's materials and surface are attractive and remain attractive throughout time to its user</u> • *Product should physically age well and develop a tangible character throughout time and use*

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4. Curiosity **a. Innovativeness** **b. Upgradability**	a. <u>Product triggers user's curiosity through innovativeness</u> • *Product should have functions, applications and uses that are novel to its user* • *Product should have functions, applications and uses that are sufficiently complex to challenge its user* • *Product should facilitate opportunities for its user to explore and discover its specificities* b. <u>Product can be upgraded by its user over time</u> • *Product's design should allow upgradability of components, functions and services* • User should have the opportunity to complement product with innovations of existing components, functions and services • User should have the opportunity to add entirely new components, functions and services to current product
5. Consciousness **a. Product-user interaction** **b. Comfort of use**	a. <u>Product facilitates interaction with its user</u> • *Product-user interactions should enhance user's attachment to product* • *Product-user interactions should trigger user's curiosity with regard to product* • *Product-user interactions should enhance user's understanding of product* • *Product-user interactions should make physical properties of products more (or at least not less) attractive* b. <u>Product offers user comfort</u> • *Product should be comfortable to use and satisfy user's needs for comfort and pleasure* • User should be at ease when using the product; using product should not bring user any trouble
6. Trust **a. Quality** **b. Safety**	a. <u>Product has and maintains high level of quality over time</u> • *User should believe in the product's ability to deliver high-quality performance* • *User should believe in product's long-term high-quality performance* b. <u>Product has and maintains high level of safety over time</u> • *User should be able to trust that product use is safe* • *User should be able to trust that product use is safe in the long term*
7. Economy of use **a. Profitability**	a. <u>Product is profitable to use over time</u> • *User should be able to profit from using product* • *User should be able to profit from using product for as long as possible* • *User should benefit from using product with regard to purchasing other products, components, additions to product etc.*

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2. Durability

Focus points	*Product design guidelines*

1. Enhanced product durability
a. Degradation-resistant materials
b. *Ruggedization* of product
	a. Product is made of materials that are resistant to degradation (corrosion, erosion, fatigue, wear etc.)
	• *Materials used for manufacturing of product should be chosen on the basis of product-user interactions and product-use environment*
	• *Materials should be tested with respect to exposure to light, water, wind, salts etc.*
	• *Coating, paint, or plating should not be used in product*
	  • They need to be maintained to keep them in good condition
	b. Product is made of materials that are stronger, less easily damaged, and last longer
	• *Materials used for manufacturing of product should be chosen on basis of product-user interactions and product-use environment*
	• *Materials should be tested with respect to shock and vibration impacts*
	• *Robust interfaces between components should be designed*
	  • The interaction between components has strong influence on the reliability of the system

2. Product optimization **a. Manufacture process** **b. Assembly process** **c. Installation process**	a. Manufacturing process of product is optimized • *Materials used for manufacturing should be treated more carefully during process* • *Materials and mechanisms used in manufacturing should be tested appropriately and frequently* b. Assembly process of product is optimized • *Assembly process should be adjusted to become more swift and effective* • *Assembly method should be altered to facilitate more favorable product assembly process* • *Component design of product should be altered to facilitate more favorable product assembly process* c. Installation process of product is optimized • *Materials used during installation of product should be adjusted or altered to facilitate more favorable installation process* • *Methods applied during installation of product should be adjusted or altered to facilitate more favorable installation process* • *Staff installing product should be altered or educated more appropriately and frequently to prevent mistakes*

3. Professionalization of post-purchase services
a. Maintenance services
b. Ease of inspection
	a. Maintenance of product is optimized
	• *Maintenance services should be professionalized and made more accessible to clients*
	  • Repair services should be offered to cure early failures
	  • Update software of original product should be offered
	  • Related product components should be modularized to facilitate easier fault analysis and maintenance
	b. Product inspection is optimized
	• *Product should be made capable of ready inspection*
	  • Manufacturing and assembly processes/methods should be adjusted to facilitate easy inspection
	  • Product inspection should be made accessible to users

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4. Product simplification **a. Product use** **b. Components**	a. Product use is simplified • *Product mechanisms and product uses are made less complex and more accessible for users* b. Product components are simplified • *Components of product should be made less complex and more accessible for manufacturing, maintenance and inspection* • *Limit the number of components by eliminating the non-essential ones*
5. Product specification **a. Product use** **b. Components**	a. Product use is specified • *Product mechanisms and product uses should be evaluated, worked out in more detail and optimized* • Mechanisms and product uses should be tested more appropriately and frequently • Avoid unnecessary movements within product b. Product components are specified • *Components of product should be evaluated, worked out in more detail and optimized* • Components of product should be tested more appropriately and frequently • Standard components of product should be optimized specifically to limit product failures
6. Replacement **a. Product components** **b. Product materials**	a. Product components are easily accessible for potential replacement • *Product should be redesigned to accommodate easy accessibility of components in case of required replacement* • These components should be modularized • *Product components particularly vulnerable for failure should be especially easy to access to facilitate replacement* • These components should be modularized b. Product materials are optimized • *Materials should be used that are easier to replace if required* • *Materials should be used whose quality is most reliable*
7. Reducing variability **a. Materials** **b. Component standardization**	a. Product material use is of limited variability • *Materials used in product should vary limitedly with respect to chemical and physical aspects and conditions so as to reduce failure of materials used* • Materials and material composition/combination should be tested more appropriately and frequently b. Product components are standardized where possible • *Components that are used multiple times should be standardized with regard to chemical, physical and geometric properties*
8. Design for understressed use **a. Product components**	a. Product components are designed for understressed use • *Components of products should normally not be operated at their maximum conditions; this prolongs their lifetime*
9. Redundancy **a. Product components**	a. Product components are made redundant • *Product components that are crucial to product's functioning should be duplicated to reduce 'work load' of these components* • Standby systems or components should take over the operation of product when required • Components and subsystems should be used in parallel to distribute workload equally

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3. Standardization & Compatibility

Process steps	*Guidelines and guiding questions*

1. Determining whether product compatibility is desirable	• Is interchangeability of product components or systems favorable?
	  ○ What benefits are served if components can be interchanged with other products (from competitors)?
	  ➢ More opportunities for application of the product
	  ○ What are the drawbacks of producing interchangeable products or components?
	  ➢ Decreasing market share
	  ➢ Association with other products and brands
	• Is there a sufficiently interesting opportunity to become a 'leader' within the market by introducing a compatible product?
	  ○ What will be the impact of the introduction of the product or component on the current market?
	• How innovative is the new technology that will be introduced?
	  ○ Is it likely that this technology will be adopted rapidly by consumers?
	• Is mass production and mass customization desirable for this product from financial and/or market share perspective?
	  ○ If so, will mass production and mass customization be successfully achieved with product compatibility?
	• Is ease of communication among users in the same product network or system favorable?
	  ○ What are the advantages and disadvantages of such cross-network and/or cross-system communication?
	• How large and promising is the current *installed base* of the product for which a compatible product or component would be designed?
	  ○ Is the current number of users sufficiently large to promise ready consumption of new compatible product or component?

2. Determining the type of product compatibility	• What kind of compatible product or product component is most favorable?
	  1. New product as a whole
	  2. New product component as a whole
	  3. Product component that can be added to an already existing product system of the producer
	  4. Product component that can be purchased and combined so as to form a product system; this involves components of more than one producer

3. Determining the most optimal way to obtain product compatibility	• How can this compatible product or product component best be obtained?
	  1. Designing product or product component in such way that it is compatible with existing production standards (figure 1)
	  2. Designing product or product component in such way that it is directly compatible with other products or product components
	  ➢ Compatibility through similarities of inherent product or product component characteristics (figure 2)
	  ➢ Compatibility through integration of a convertor in the product or product component (figure 3)
	  ➢ Compatibility through an external converter between the products or product components that are to be made compatible (figure 4)
	  3. Use of product modularity
	  ➢ Compatibility of products through modularizing product components and product systems

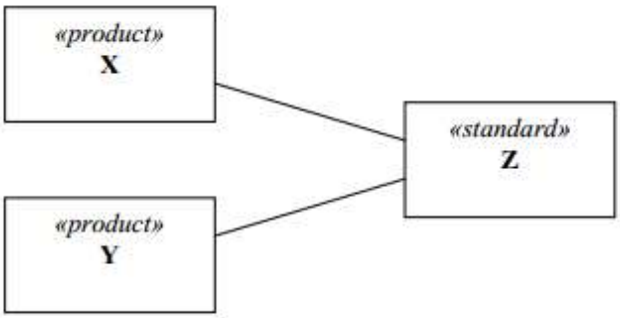

Figure 1. Compatibility between different products and existing production standards (based on Succi et al., 1998).

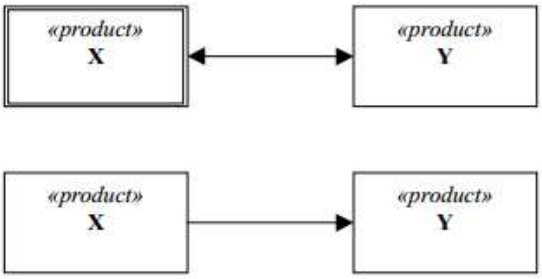

Figure 2. Compatibility between products through similarities of inherent characteristics (based on Succi et al., 1998).

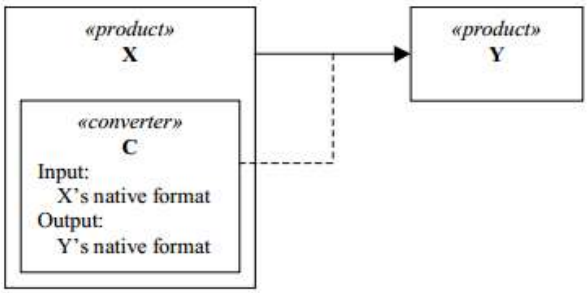

Figure 3. Compatibility between products through integration of a converter possessing characteristics of both product X and Y (based on Succi et al., 1998).

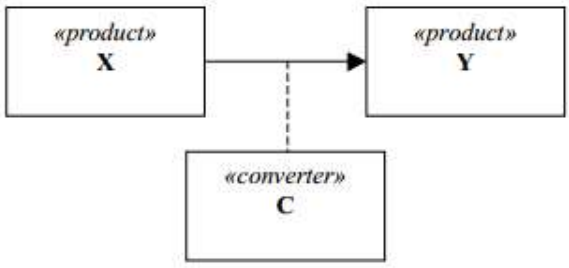

Figure 4. Compatibility between products through inclusion of an external convertor in their connection (based on Succi et al., 1998).

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4. Ease of Maintenance & Repair

Focus points	*Product design guidelines to enhance maintainability and supportability*

General guidelines	• *Design equipment in such way that it can only be maintained in the right way*
	  ○ Unambiguous design induces little mistakes during maintenance activities
	
	• *Design the system in such a way that adequate forecasting of maintenance is possible*
	  ○ Little variability in mean times to failure of components enables preparation of an adequate maintenance planning
	
	• *Design the weakest link*
	  ○ Weakest link in every system should be relatively cheap and easily replaceable component
	
	• *Use standard interfaces*
	  ○ To enable quick connection between and interchangeability of modules and sub-systems
	
	• *Guarantee safety by design itself*
	  ○ Instead of using warning labels and colour codes
	
	• *Make the product testable*
	  ○ Reactive (fault finding) tests often reveal latent problems that will become faults in the near future
	  ○ Build self-use and diagnostic routines into complex data-oriented products and systems
	
	• *Avoid that secondary tasks consume a lot of time*
	  ○ The main activity is executing maintenance
	
	• *Do not use materials that affect user's and technician's health*
	  ○ Avoid corrosive chemicals for lubricants and cleaning products
	
	• *Build monitoring equipment into the system*
	  ○ In order to know if maintenance needs to be executed and to reduce the time for isolating faults

Handling & access	• *Ensure that operators of installations are also able to maintain them*
	  ○ Maintainable equipment is often user-maintained
	  ○ Design for the use of standard tools
	  ➢ Avoid the requirement for special maintenance tools so that every technician is able to execute maintenance tasks
	  ○ Personnel with a variety of backgrounds should be able to execute maintenance
	  ○ Provide understandable maintenance instructions
	
	• *Ensure that as few as possible technicians are required to perform maintenance task*
	  ○ Fewer personnel has to be available at the moment maintenance needs to be executed
	
	• *Provide sufficient space around the maintenance points*
	  ○ Maintenance personnel should be able to execute maintenance with good posture
	  ○ Ensure that there is enough room to maneuver parts and tools into position without causing secondary damage

	• *Position the maintenance points close to each other*
	  ○ Maintenance location is known beforehand
	
	• Large modules should be mounted on hinges, slides, or runners
	  ○ This allows them to be pulled or swung into position offering better all-round access
	
	• *Consider handling and lifting of modules or components*
	  ○ Show location of e.g. grab handles and lifting eyes

Modules & Joining mechanisms	• *Design modular systems*
	  ○ Enables easier fault analysis and maintenance
	  ▪ Enables complete replacement of a broken module to repair it at a different place
	  ▪ Allows for greater interchangeability of components
	
	• *Use fasteners that accelerate maintenance activities*
	  ○ Do not use permanent fastening techniques (adhesive fastening, riveting, welding) where separation is required for maintenance
	  ○ Ideally no tools required to open/remove components
	
	• *Minimize the number of fasteners required*
	  ○ Smaller number of fasteners facilitates easier dis- and reassembly in cases of maintenance and repair; eliminates chances of losing materials required for fastening
	
	• *Select fasteners with regard to the replacement frequency of concerned components and availability of tools at replacement location*
	  ○ Facilitates easier, quicker and more careful removal and replacement of components

Components & Materials	• *Use standard, universally applicable components*
	  ○ Reduces maintenance, breakdown, and replacement costs
	  ▪ Components are widely understood; easy to maintain by users or technicians
	  ▪ Increased possibility of component replacement
	  ▪ Increased interchangeability of components
	  ▪ Easier disassembly
	
	• *Use components that function within the entire specified dimensional tolerance band*
	  ○ This prevents components to be too specifically tailored to certain conditions
	
	• *Components that are regularly replaced need to be easy to handle*
	  ○ Standard size and weight, no sharp edges, easy to transport
	
	• *Position components that often need to be maintained at an easily accessible place*
	  ○ Location of components could be based on number of times they need to be maintained (e.g. at outer edge of product in case of frequent lubrication or visual inspection)
	
	• *Use materials that do not prolong maintenance activities*
	  ○ Avoid non-corrosion resistant materials in moist environments
	
	• *Avoid that expensive spare parts need to be held in stock*
	  ○ In order to reduce the inventory costs

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5. Upgradability & Adaptability

Product design steps	*Corresponding product design guidelines*
1. Defining a long-term *upgrade-and-adapt plan* for the product among several generations *Key overarching question:* ➢ Which product functions will have to be upgraded or adapted in each product generation?	• **Determining the product functions of the current product** *Key question:* ➢ What are the various product functions of the current product and how are they interconnected? ▪ <u>The most relevant steps in this phase are:</u> 1. *Listing all major product functions* ➢ The product should be 'broken down' in compartments so as to analyze all major functions of the product. 2. *Function decomposition* ➢ The major functions of the product should be worked out in further detail so as to formulate product subfunctions (*function decomposition*). ➢ The type and nature of the relations between the relevant functions and subfunctions of the product should be outlined. 3. *Selection of physical features* ➢ The physical features of the current product should be analyzed and checked for compatibility with the product's functions and subfunctions. • **Determining scenarios of future product change** *Key question:* ➢ What are the relevant changes of the product's functions in the future? ▪ <u>Three different types of product information should be obtained:</u> 1. *Information on product use and product-user interactions* ➢ Used products should be taken in and analyzed so as to gather information on the relevant physical effects that the product use has on the product. ➢ Product users should be consulted and interviewed so as to gather information on the relevant product-user interactions. 2. *Information on technological developments* ➢ What current technologies are presumably the most relevant to the product's future development? ➢ How will these current technologies presumably evolve in the future? ➢ How will these future technological developments presumably impact the product, its functions, and its design? 3. *Information on developments in society* ➢ What current societal structures and settings are presumably the most relevant to the product's future development? ➢ How will these societal structures and settings presumably evolve in the future? ➢ How will these presumable future societal developments impact the product, its functions, and its design? • **Determining product functions that are to be upgraded or adapted per product generation** *Key question:* ➢ Which functions need to be upgraded or adapted per product generation as deduced from the abovementioned gathered information? ▪ <u>The selected product functions for upgrading and adaptation should be described in detail per product generation. This constitutes the product's *upgrade-and-adapt plan*</u>.

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2. Determining upgrading and adaptation operations for each product generation *Key overarching questions:* ➢ How can the product be upgraded through: 1) altering its functions; 2) altering its performance in each generation? ➢ How can the product be adapted to serve multiple functions throughout its lifetime?	• **Functional upgrading: determining how the product can be upgraded through altering its functions** *Key question:* ➢ How can the selected product functions in step 1 be upgraded? ▪ <u>There are two main ways in which functional upgrading can be incorporated into a product:</u> 1. *Making functions independent of the product* ➢ This means that components or modules that are relevant to the product function that is to be upgraded should be embodied in the product design in clusters or modules. 2. *Making functions insensitive with regard to the product* ➢ This means that product components should be used whose functionality and performance are excessive to the first product generation but indispensable for subsequent product generations, thereby adding flexibility of performance to the product without future replacement of components. • **Parametric upgrading: determining how the product can be upgraded through altering its performance** *Key question:* ➢ How can the product as a whole be upgraded? ▪ <u>There are two main ways in which parametric upgrading can be incorporated into a product:</u> 1. *Making functions independent of the product* ➢ This means that product components relevant to the product function that is to be upgraded should be: 1) Adjusted so that they have a bigger performance margin than the original component versions; 2) Replaced by components that have a bigger performance margin than the original component versions. 2. *Making functions insensitive to the product* ➢ This means that product components relevant to the product function that is to be upgraded should be: 1) Adjusted so that their performance level becomes controllable and, thus, flexible; 2) Replaced by components whose performance levels are controllable and, thus, flexible. • **Functional adaptability: enhancing the extendibility of product functions** *Key question:* ➢ To what extent can the functions of the product be extended? ▪ <u>Product functions can be extended in two main ways:</u> 1. *Designing existing parts with versatile functions* ➢ Product components should be designed in such a way that they are capable of performing more than one single function. 2. *Adding or replacing parts and assemblies* ➢ Product components with high function extendibility should be added to the product's design. ➢ Product components with low function extendibility should be removed and/or replaced by components with higher function extendibility. • **Customized and operational adaptability: determining the ease of adaptability** *Key question:* ➢ How easily adaptable is the product with regard to consumer use? ▪ <u>Two factors are important for this:</u>

	1. *Customizability of the product components* ➢ The product components should be easily adaptable for individual product users. 2. *Operationability of the product* ➢ The product's interface should be convenient to use. ➢ The product users should not experience difficulty in and should feel comfortable when adapting the product to different functions.
3. Determining the platform and *upgrade-and-adapt* modules of the product *Key overarching question:* ➢ Which product components should be included in the product's platform and which should be included in the product's design as upgrade-and-adapt modules?	• **Distinguishing between the product platform and the upgrade-and-adapt modules of the product** *Key question:* ➢ Given the abovementioned upgrading and adaptation operations for each of the product generations, which product components should become part of the product platform and which components should be part of upgrade-and-adapt modules? ▪ <u>The decision whether or not to include a product component in the product platform is determined by the respective plausibility of this component being involved in upgrading or adaptation operations. There are three guidelines concerning this:</u> 1. Components that perform or are involved in upgrading or adaptation operations that are very likely to take place (*high plausibility*) should be integrated in the product platform as much as possible. ➢ This means that they become part of the common product structure that does not change throughout the various product generations. ➢ These components should have 2. Components that perform or are involved in upgrading or adaptation operations that are not very likely to take place (*low plausibility*) should be isolated from the product platform. ➢ This means that they will be used as upgrade-and-adapt modules, being added to, replaced, removed from or adapted to the product platform when required. ➢ By doing this, it is avoided that these components are part of the common product structure without being required in subsequent product generations. 3. *Delayed selection of components* ➢ This means that the product should include entities with components that have different performance levels, so that the appropriate components can be chosen once the product is upgraded to a next generation or adapted.
Component standardization & Product modularity	• **Standardization and modularization of product components can significantly enhance a product's upgradability and adaptability** ▪ <u>Benefits of component standardization with regard to product upgradability and adaptability:</u> ➢ Standardized and modularized components are highly interchangeable, which enhances the replacement of components or modules and, thus, facilitates the introduction of upgraded and adapted products and increases the number of potential product variants. <u>This can be done in two main ways:</u> 1. Upgrade-and-adapt modules should be standardized where possible so as to facilitate interchangeability and to increase the speed and ease of adding or replacing. 2. Components that are related to each other with regard to a certain product function should be modularized so as to enhance the processes of adding, replacing or removing components from the product platform.

6. Dis- & Reassembly

Benefits	*Product design guidelines*
Less disassembly work	• Use standardized and modularized components • Combine elements that are of same material • Use compatible materials • Limit material variability • Minimize number of joining elements • Modularize harmful materials into subassemblies • Provide easy access for harmful, valuable and reusable parts • Provide easy access to disjoining, fracture or cutting points
Predictable product configuration	• Avoid ageing and corrosive material combination • Protect subassemblies against soiling and corrosion
Easy disassembly	• Use standardized and modularized components • Accessible drainage points • Use joining elements easy to remove or destroy • Standard and simple joining techniques • Marking of central joining elements for disassembly • Minimize number of fasteners • Use the same fasteners for many parts • Provide easy access to disjoining, fracture or cutting points • Avoid multiple directions and complex movements for disassembly • Linear and unified disassembly direction • Avoid turning operations for disassembly • Enable simultaneous separation and disassembly • Base part product structure • Set center-elements on a base part • Avoid metal inserts in plastic parts
Easy handling	• Leave surface available for grasping • Avoid non-rigid parts • Enclose poisonous substances in sealed units • Parts should be easily stored and transported
Easy separation	• Use standardized and modularized components • Avoid secondary finishing (painting, coating, plating etc.) • Provide marking or different colours for materials to separate • Avoid parts and materials likely to damage machinery
Variability reduction	• Use standardized and modularized components • Minimize number of fastener types • Limitation to the number of different materials • Standardize parts for multiple use

Reassembly of parts, unit or complete products is made easier and more effective when they adhere to the abovementioned requirements. Most relevant aspects are:

- Use of standardized and compatible parts, units and materials
- Use of modularized parts, units and subassemblies
- Minimize the variety of parts, units and subassemblies
- Limit material variability
- Simple and easy-to-replicate product structure
- Linear and unified assembly direction

Assembly methods

- An overview of the various principles and characteristics of connections of product materials has been presented in a dissertation of Kuo (1997) (see table 2.1). This can be a useful tool for designers in evaluating the feasibility of a certain connection with respect to ease of dis- and reassembly.

Table 2.1. Assembly method table (redrawn from VDI 1993).

principle of connection / characteristics of connection		Material Connection		Friction Connection					Positive Connection					
		plastic/metal adhesive bonding	welding	magnetic connection	Velcro fastener	bolt/ nut	plastic bolt/ nut	spring connection	snap joint	bent-lever connection	1/4 turn fastener	press turn fastener	press-press fastener	band with lock
Carrying Capacity	Static Strength	◐	●	◐	○	●	◐	◐	●	●	●	◐	◐	●
	Fatigue Strength	◐	●	◐	○	●	◐	○	◐	◐	◐	◐	○	◐
Joining Behavior	Joining Expenditure	◐	◐	●	●	◐	◐	●	●	●	●	●	●	●
	Guidance Expenditure	○	○	◐	●	◐	◐	●	●	◐	●	●	●	◐
Detaching Behavior	Non-destructive detaching Expenditure	○	○	●	●	◐	◐	●	○	●	●	●	●	◐
	Destructive detaching Expenditure	◐	◐			◐	●		●	◐	◐	◐	◐	●
Recyclability	Product Recycling	○	○	◐	◐	◐	●	●	○	●	●	●	●	●
	Material Recycling	◐	●	◐	◐	◐	●	●	●	●	●	◐	◐	●

● good ◐ average ○ bad

Source: Kuo, 1997, p. 14.

Assembly hierarchies

- A clear visual representation of the different *levels of assembly*, or the *hierarchies of assembly*, is given in a study performed by Xiaoyan et al. (2009) (see figure 1). It is of key importance to be aware of the hierarchical assembly structures involved when (re)designing a product with the aim of making it easier to dis- and reassemble.

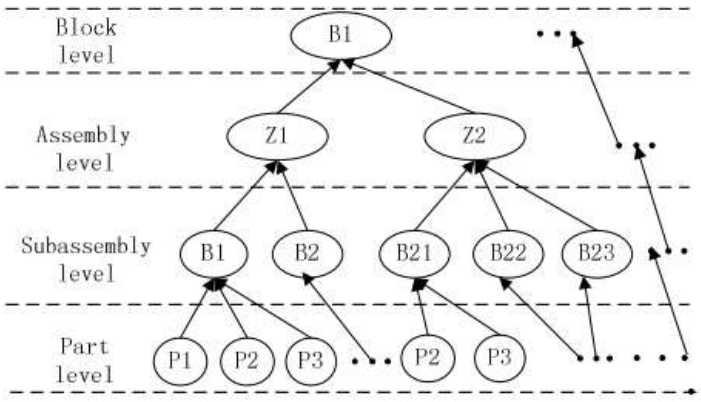

Figure 1. The hierarchical assembly structures

Source: Xiooyan et al., 2009, p. 789

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3. Standardization & Compatibility

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