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DESIGN FOR POKA-YOKE ASSEMBLY AN APPROACH TO PREVENT ASSEMBLY ISSUES

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1. Introduction

It is important to be aware about assembly quality issues (aq-issues) due to they represent a significant proportion of quality defects in many companies [Kenger et al., 2005]. Assembly quality issues are commonly analyzed after they occur and it is observed that best solutions to eliminate these issues are performing a poka-yoke or error-proofing redesign in the product. The poka-yoke or error proofing technique developed by Shigueo Shingo [Shingo et al, 1990] has been successfully used to reach zero defects on many companies, this technique help to prevent the occurrence or detect on time defective parts during manufacturing or assembly processes; these improvements are possible by means of product or process design changes [Shimbun, et al, 1990].

The approach developed in this paper is oriented to analyze potential aq-issues before start mass production in order to design for poka-yoke assembly since early product design stages and avoid later redesigns.

According to aq-issues described in Estrada there are sixteen aq-issues referred as “A_x” that are potential to occur in complex mechanical products during overall life phases of a product or system [Estrada et al., 2007] for example in system production phase can occur an aq-issue called “incorrect assembly position of parts”, see this example in figure 7; complete list of A_x are showed in figure 2.

This work is focused in define how designers can identify since early design stages the potential aq-issues, in order to establish since task clarification design stage, as part of the customer requirements list, the assembly design requirements that has to be complied to design a product for a poka-yoke assembly. During conceptual, embodiment and details design stages the approach developed will provide designers the specific poka-yoke assembly design requirements that must be considered to obtain a product design with features oriented to prevent assembly issues, bringing benefits not only to final users also to assembly operators, manufacturing and quality engineers, technicians who install or give maintenance to product. The poka-yoke assembly design requirements mentioned in this paper are referred to seventeen design requirements list that were developed in Estrada [Estrada et al., 2007] these requirements are referred as “R_x”(see section 4).

In order to evaluate how useful can be this approach if it is applied on the industry, this research was discussed with a company that design and manufacture mechanical products. In section 6 is described the results of an interview performed to a senior quality engineer who declared that He was involved in two new product developments projects and in both projects redesigns were performed to eliminate an assembly issue presented during mass production. In section 6.1 is analyzed how those redesigns could be avoided if DFPYA approach would be used since task clarification stage.

2. Design for assembly quality

Das propose an approach to evaluate in a product which components have more possibilities to present aq-issues based on key product design factors, these are: i) factor variables and ii) influencing factors [Das et al., 2000]. In Design for Poka-Yoke Assembly approach these type of product design factors are considered as design characteristics (C_x) and they are defined based on decisions that designers made during design process, for example: to define product architecture, select type of material, decide parts size, shapes of matting face etc., (see complete list of eleven C_x in figure 2).

Booker defines two main causes that impact on final assembly quality of product i) components design decisions and ii) assembly technology selection; these authors assign a value to different type of decisions made in a component design, for example it is asked if a specific component can be assembled in a wrong way, if the answer is "yes" the value is 2.0 and if the answer is "no" the value is 1.0, at the end of the analysis components with higher value means that need to be redesigned [Booker et al., 2005].

Another important contribution in design for assembly quality is Güngör, this author proposes a model to evaluate alternative connectors that helps designers to make better decisions when selecting product connectors [Güngör, 2006]. The criteria used for this evaluation is key to prevent aq-issues such as: A_1 product damaged, A_{10} difficult inspection and test activities, A_{13} operation assembly failures, A_{14} difficult to assemble/disassemble for maintenance, A_{16} difficult disassemble for recycling or further use (see figure 2).

The design for assembly quality approaches that exists are based on evaluate assembly quality in a product that was already designed to identify which components must be redesigned to improve quality assembly level acceptability; the approach presented in this paper is focused to prevent redesigns by complying with R_x that are oriented to avoid aq-issues since early design stages.

3. Methodology Research

Research developed respond to the following questions: i) what is the earliest design stage where it is possible to identify potential aq-issues? ii) How can designers know what the best stage is to comply with poka-yoke design requirements "R_x"? iii) What activities should be performed by designers during product development process in order to assure that product was designed for a poka-yoke assembly?.

To respond these questions it was classified the R_x (see section 4.1); then based on design process approach of Pahl and Beitz [Pahl et al., 1996] it was established the appropriate process design stage where R_x can be applied (see section 4.2).

Based on method used to perform a FMEA analysis [Stamatis, 1995] it was defined five general steps oriented to realize an aq-issues risk analysis (see section 5.1). Also it was reviewed the corresponding activities performed during product design method [Pahl et al., 1996] to identify where and how designers could comply with these five steps (see section 5).

4. Design requirements for poka-yoke assembly and product design process

Seventeen design requirements for a poka-yoke assembly, that are necessary to satisfy assembly quality expectations of customers and professionals, were established in Estrada; these requirements were developed to guide designers to orient product design process to prevent aq-issues [Estrada et al., 2007] but this approach did not specify in which stage of process design these requirements has to be used.

In these seventeen poka-yoke design requirements is observed that based on knowledge required to comply with each of this R_x some of them can be satisfied since conceptual design but others must be considered during embodiment or details design stages. To determine in which stage can be complied each specific requirement it was analyzed the type of decisions that are taken in each process design stage and it was evaluated how these decisions affects to comply with poka-yoke design requirements.

4.1 Classification of poka-yoke assembly design requirements

Following are briefly defined and classified the seventeen R_x, according to type of decisions that designers make during process design, these decisions are: i) establish product architecture ii) type of material selection, iii) fastening method selection, iv) part features design, v) tolerance allocation, vi) assembly sequence decision. In figure 1 is showed the R_x classification based on these six categories.

Poke-Yoke assembly design requirements (Rx) Classification	
PRODUCT ARCHITECTURE DEFINITION	**TYPE OF MATERIAL SELECTION**
Define modular product oriented to be safety and easy assemble and disassemble product to:	*Select parts material properties oriented to:*
R_1. Inspect and test product during assembly operations.	**R_4.** Resistance to assembly devices.
R_2. Change product configuration and give maintenance to product.	**R_5.** Be flexible to easily insert parts by hand.
R_3. Remove modules for recycling or further use.	
PART FEATURES DESIGN	**FASTENING METHOD SELECTION**
Design features in parts oriented to:	*Design parts oriented to:*
R_7. Just correct assembly is possible due to matting faces design.	Comply with: R1, R2 and R3.
R_8. Be used by poka-yoke detection devices.	**R_6.** Integrate small parts in bigger parts to reduce quantity.
R_{10}. Do not look symmetrical when they are not.	**R_9.** Use appropriate fastening methods to reduce effort for manual assembly.
R_{11}. Bring stability to part face in contact with assembly device.	
R_{17}. Integrate alignment specification into dimensions of parts.	
TOLERANCE ALLOCATION	**ASSEMBLY SEQUENCE**
Allocate tolerance in parts considering the following:	*Design assembly sequence in order to:*
R_{14}. Not excessive effort to manual parts insertion.	**R_{12}.** Assemble small parts after free access are enclosed.
R_{15}. Comply to alignment specifications.	**R_{13}.** Assemble a part after assure that other assemble operations will not damage it.
R_{16}. Variations of materials during life cycle stages.	

Figure 1. Classification of poka-yoke assembly design requirements-R_x

4.2 Design process analysis

Based on design process systematic approach by Pahl and Beitz it was identified what design stage correspond to design decisions classification by asking questions, for example: "In what design stage is decided the product architecture?" responding to this example it was observed that decision about definition of product architecture is performed during design concept stage, therefore according to R_x classification R_1, R_2 and R_3 can be considered in concept stage. See figure 1 and 6.

5. Design for poka-yoke assembly approach

DFPYA approach covers three key objectives; 1) perform an aq-issues analysis during product design process, 2) identify the design stages to comply with poka-yoke assembly requirements, 3) evaluate if potential aq-issues identified were avoided as expected. Based on analysis performed in previous sections; following are described the activities that have to be realized to design a poka-yoke assembly product. See diagram of DFPYA approach in figure 6.

5.1 Assembly quality issues risk analysis

Based on risk analysis techniques to eliminate failures in product such as FMEA [Stamatis, 1995] there are five general steps that has to be followed to perform this type of analysis; these steps are: a) list of operation steps, b) identify potential failure modes for each operation step, c) identify root cause of failures, d) establish priorities by evaluating severity, probability of occurrence and failures detection and e) define actions to mitigate these causes. In this work these steps were oriented to comply with purpose of avoiding aq-issues since early process design stages, these steps were redefined as: i) identify assembly expectations for each product life cycle stage, ii) identify potential product aq-issues, iii) establish priorities to avoid potential aq-issues based on effects severity that they can cause in product life cycle stages, iv) identify root cause of assembly issues associated to product design characteristics and v) define actions: use of poka-yoke design requirements that avoid the occurrence of aq-issues.

The approach developed indicates the activities that must be performed to design a product for a poka-yoke assembly; in the first stage of clarifying the task designers will be able to establish a priority of R_x; this step covers the activities i), ii) and iii). The last two activities iv) and v) are already covered by R_x due to these requirements were established based on experience described in literature and company surveys where a similar aq-issues were solved by performing a redesign in a specific C_x; see figure 2. The figure 2 relates in a matrix the design characteristics C_x that should be modified to comply with poka-yoke requirements R_x to prevent since early design stages specific aq-issues A_x.

		Potential quality assembly issues-**Ax** that can occur during life phases of a system															
		System Production										System Installation		System Operation			S. Replacement
		Product damaged	Difficult to alignment parts	Instability in dynamic parts	Incorrect assembly position of parts	Wrong part assembled	Omission of part(s) during assembly	Parts trapped inside the product	Ergonomic issues to assembly parts	Improper fasten of parts	Difficult inspection and test activities	Wrong installation of parts	Damages of part during installation	Operation assembly failures	Difficult assy. for maintenance	Assembly configuration issues	Difficult disassemble for recycling-further use
Cx: Design Characteristics		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16
C1	Product architecture										R1				R2	R2	R3
C2	Type of material	R4,R5		R4					R5	R4			R4	R4			
C3	Parts size						R6	R6									
C4	Matting face				R7,R8	R7,R8						R7				R7	
C5	Part features		R17		R7,R8	R7,R8	R8					R7				R7	
C6	Type of Fastening	R9							R9	R11			R9		R9		R9
C7	Part symmetry				R10	R10						R10				R10	
C8	Contact surface to assemble	R11											R11		R11		R11
C9	Assembly sequence	R13						R12					R13				
C10	Tolerances		R15	R16					R14	R16				R16			
C11	Similar appearance parts				R8	R8						R8					

Figure 2. Matrix of poka- design requirements-R_x to prevent aq-issues-A_x by orienting product design characteristics-C_x, source [Estrada et al., 2007]

5.2 Priority of poka-yoke assembly design requirements

During task clarification stage the product development team has to identify potential aq-issues and corresponding poka-yoke assembly design requirements that apply to product in development to avoid the occurrence of assembly issues and define a prioritization of these requirements. To perform this task the following specific activities have to be performed.

5.2.1 Potential A_x related to customer and professionals expectations

In a concurrent engineering environment it is important to consider besides of customer needs the professionals needs [Prudhomme et al., 2003]; to identify these needs has to be identified first who are these customers and professionals and corresponding product life cycle stages where they are present. In figure 3 is showed and example of customers and professionals of a product during system life cycle phases and their common assembly expectations.

According to assembly expectations that were identified, designers must evaluate corresponding potential aq-issues that can be experienced if some expectations are not satisfied by product in development.

5.2.2 Identify poka-yoke assembly requirements R_x that apply to assembly issues A_x

Based on aq-issues that were determined as potential to occur in product been developed designers have to select from matrix showed in figure 2 the applicable R_x that has to be considered to avoid these A_x.

System life cycle stages	System production (Manufacture, Assembly test)	System Installation (Sales, Service, Distribution)	System operation (Operation, Consumption, Maintenance)	System Replacement (Recycle, Further use, Environmental disposal)
Customers & professionals assembly expectations	**Assembly operators:** Ergonomic assembly operations **Quality Engineers:** Poka-yoke components to correct assembly.	**Product installers:** Easy to assembly, safety assembly, poka-yoke parts to correct assembly	**Final Users:** Easy to assemble parts to change configuration, robust parts assembly in case of inappropiate movement of product.	**Product disposers:** Safety and easy to remove recycle materials.

Figure 3. Example of customers and professionals expectations during system life cycle stages and common assembly expectations

5.2.3 Evaluate priority of R_x

Prioritization of assembly requirements will help to decide in next stages when two or more requirements can not be fully satisfied because main design requirements are compromised. When a poka-yoke assembly requirement can not be complied during design process the corresponding aq-issues that are not prevented have to be analyzed during manufacturing process design for this reason it is important to keep a traceability of aq-issues analysis during each stage of process design see section 5.3. To evaluate the priority of R_x a similar FMEA method can be used, in column F, G and H values from 1 to 10 are used to quantify design suitability of requirements (F), A_x severity (G) and A_x occurrence expectations (H). See figure 4. In section 7 is suggested who can perform this evaluation.

A. Life cycle system stage	B. Customer description	C. Customer assembly expectations	D. Potential Ax	How easy is to orient product design to comply with this Rx? ⇨ / E. Corresponding Rx	F. Rx Design suitability	G. Ax Severity	H. Occurrence expectations of Ax	I. Rx Priority Number
System Production	Assembly operators	Ergonomic assembly operations	A8	R5: Flexible material to easy manual insertion	3	6	5	(6)(5)(3)=90
				R9: Fastening method- Low effort to insert	8	6	5	(6)(5)(8)=240
				R14: Enough tolerance for manual insertion	5	6	5	(6)(5)(5)=150

Figure 4. Example to evaluate R_x priority

5.3 Tracking of assembly quality issues analysis

Penock et al, 2002 mention that it is important in a project risk management process to track the status about the effectiveness of strategies established to manage the set of risk identified; in the same way in this approach is observed this need because designers have to take care about many information during new product development process and it is possible that during this process they can omit or forget to analyze a specific R_x and they can cause with these mistakes that a potential A_x was not avoided as expected. To assure effectiveness of those strategies established to mitigate causes of identified risks it is important to use risk metrics to measure the state of a key subsystem or component of the project [Penock et al., 2002]; in this approach is suggested to use a special data sheet to record all tasks to perform the aq-issues risk analysis. This data sheet, showed in figure 5, as minimum has to content design process stage (column A), specific A_x been analyzed (column B), applicable R_x (column C), priority of R_x (column D), comments about action taken to prevent a A_x (column E), C_x that will be modified (column F), location drawing reference that show design features oriented to prevent A_x (column G), pending tasks (column H) for example in this column H can be written if A_x was decided to be avoided during manufacturing process stage. See figure 5.

A. Design Stage	B Ax	C. Rx	D. Priority Rx	Actions taken			H. Pending tasks for next stages
				E. Comments	F. Cx	G. Design Ref. Number	

Figure 5. Data sheet to record task of aq-issues-A_x analysis

5.4 Physical test to validate poka-yoke assembly features designed

An important step in this approach is to perform a physical assembly test with a prototype product in order to assure that features designed to prevent aq-issues works as expected or identify if there are components that need design changes; the results of this test must be recorded in data sheet showed in figure 5, column E and H.

5.5 Assembly quality issues evaluation

After conclude previous step a question is asked by designers: Potential aq-issues were avoided as expected? this question is very important to detect if a aq-issue was not analyzed because it was omitted by error or it was not possible to apply corresponding poka-yoke requirements due to some constraints; if there is a constraint that does not allow apply a R_x in the product it can be decided to prevent the corresponding A_x by a poka-yoke device in manufacturing process. In order to evaluate how efficiently the poka-yoke assembly design requirements were applied during design process an evaluation has to be realized by checking records in data sheet (figure 5) for each A_x to assure if actions taken in product design will be able to prevent the issue.

5.6 Update new poka-yoke assembly knowledge into design process procedures

Each decision that designers made to design a feature with a specific characteristic to comply with a poka-yoke assembly requirement results in new knowledge that it is useful for product in development but it does not mean that in future designs this important new "poka-yoke assembly knowledge" will be used. It is recommended that designers capture this new knowledge as design rules and document them in design procedures to be followed by the company each time that a new product is developed.

6. Industry case study

The DFPYA approach developed was presented to a company that design and manufacture mechanical products; in this section is described the results of an interview performed to a senior quality engineer from this company that was involved in two new product development projects. He was asked the following questions: i) Are there some examples of assembly quality issues that company solved by redesigning the product?, ii) Could you explain those cases?.

The quality engineer explained one case of assembly issue in a recent new product developed and two cases of assembly issues in other new product development project that were solved by redesigning a component. Following is described only an example of these issues.

The assembly quality issue was that due to human mistakes the assembly operators inserted a component "A" in incorrect position and defective products were detected at the end of the process by quality inspectors, see figure 7. In order to eliminate this issue in a poka-yoke way and eliminate 100% inspection in the production line, a component "B" was redesigned in a way that is impossible to insert component "A" in wrong position, see figure 7.

6.1 Analysis of industry assembly quality issue and redesigns

The aq-issue described is an example of the issue classified as A_4: incorrect position of parts. This aq-issue could be avoided if designers since task clarification stage identify that it is possible to assemble parts in incorrect position, they can suspect about this issue because they should know that company will use manual assembly operations. Therefore according to DFPYA approach designers should consider during embodiment design stage when they are defining specific part features the poka-yoke assembly design requirement (R_x) associated to aq-issue A_4, these R_x are R_7, R_8 and R_{10}. The poka-yoke redesign developed by the company to avoid A_4 issue match with R_7 definition (see R_7 definition in figure 1). This example shows that by following poka-yoke philosophy, efficient redesigns can be developed to prevent aq-issues, but as everybody knows redesigns are expensive, it would be cheaper to design the feature in component B since the first time the product was designed. DFPYA approach assist designers to think in poka-yoke solutions since the first time they are developing the product, avoiding with this practice later redesigns.

7. Discussion

The approach that is proposed in this paper requires to product development team since task clarification stage to collect information from different company departments to be aware about assembly issues presented in similar company products, also they will need information from external sources such as final users to know the assembly expectations. Specific surveys can be formulated to get this information from final users for example by asking what kind of assembly issues they have experienced with similar products?. Other sources that can be consulted are those related to recall issues posted in different databases to find out if similar products experienced assembly failures during system operation stage. In order to manage all information and give an efficient follow up in the application of this approach during design process it is recommended to assign a person responsible to assure that all necessary steps are performed correctly in order to avoid potential assembly quality issues defined during task clarification stage. Quality engineers are suggested to be the responsible to follow up aq-issues risk analysis due to they have the background about how aq-issues occurs, how critical and frequent those issues are, sources where company aq-issues are recorded and also they use to manage risk analysis documents such as FMEA.

8. Conclusions and future work

Based on analysis of different activities that are performed during design process, steps followed to perform a FMEA risk analysis and poka-yoke assembly design requirements it was possible to develop an approach that guide designers since task clarification stage about how they can integrate as part of customer requirement list specific poka-yoke assembly requirements that satisfy customers and professionals assembly expectations. Even these expectations are normally not declared during task clarification stage they are important because must of quality defects presented in many companies and customers complaints are related to assembly quality issues. The approach presented in this paper requires to perform additional activities during design process besides normal tasks that has to be completed to develop a new product; these activities needed to design a product for a poka-yoke assembly must be better realized by using CAD technologies; a future work in this area will be to develop a software that can aid designers to facilitate this job to assure that tasks described in the approach are correctly executed.

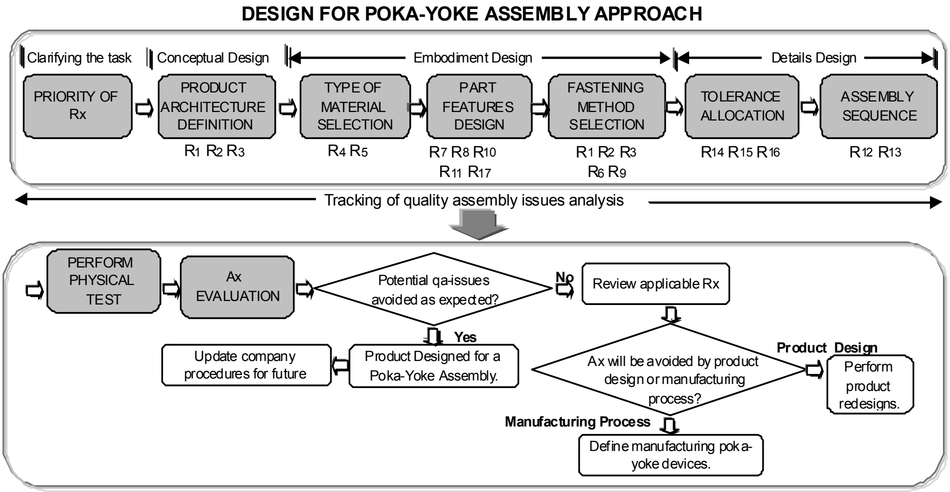

Figure 6. Design for poka-yoke assembly approach

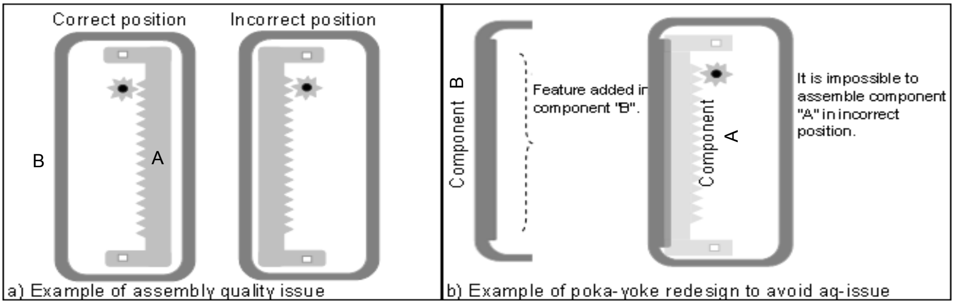

Figure 7. Example from a Company of aq- issue and poka-yoke redesign

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