A criticality analysis of kitting processes

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Abstract: A frequently adopted parts feeding policy in assembly lines is kitting, where all components needed to assemble one unit of the end item are placed inside a container to be individually delivered to the assembly line. Kitting supports the assembler's work but is penalized by relevant workforce cost for kits preparation, discouraging the use. However, recent literature highlights that kitting is a cost effective and competitive supply policy if logistic errors are considered. Nevertheless, usually kits are manually prepared. This exposes to manual error during the kit preparation phase (parts picking, counting, moving, delivering etc.), which determine product non conformities and errors correction costs. To reduce or remove the problem, error free kits are required. In this paper a dedicated innovative FMECA approach is proposed to improve kitting operations based on the main errors types occurring kit preparation. In particular, for each kit component the susceptibility to error commission based on its morphological and utilization characteristics (i.e. multiplicity, sequencing etc.) will be assessed. Then a risk priority number will be computed based on the error consequences and detectability at the assembly level (i.e. correction cost, potential harm to the user etc.). This allows to determine critical components based on their properties, and assess the components suitability to kitting. This may lead to kit redesign and improved training procedures for operators in order to reduce errors occurrence.

Keywords: Kitting, human error, FMECA, assembly lines parts supply.

1. Introduction

Kitting is a manner of feeding parts to assembly lines where all parts required to assemble one unit of the end product are grouped together and placed into one or more kit containers. Kits are prepared in a kitting area within the warehouse or nearby a parts supermarket and delivered to the assembly line, either at the start of the line (travelling kit concept) or to specific workstations (stationary kits), according to the production schedule). (Brynzèr and Johansson 1995; Bozer and McGinnis 1992; Caputo and Pelagagge, 2011; Hanson, 2012). Kitting simplifies the material flow through the shop floor as only kits need to be moved to the assembly line. It also minimizes stock at workstations saving floor space and holding cost. Kitting may thus represent a viable solution especially in case of high-mix and low-volume production in mixed model assembly lines. Moreover, kitting supports the assembler's work improving quality and productivity as parts are readily available, checked, pre-positioned in a logical order, and can be removed quickly from the container. However, kitting has the drawback of high workforce consumption owing to intensive parts picking and manual handling required for kit preparation. Another problem affecting kitting is that most kit preparation activities are carried out manually, so that human error is a relevant cause of quality problems in kitting processes.

In order to give a contribution to the design of error-free kits or to directly improve the efficiency of the kitting process, in this paper a dedicated innovative Failure Modes Effects and Criticality Analysis (FMECA) approach is proposed to improve kitting operations based on the main errors types occurring during kit preparation. FMECA is a commonly used technique allowing to identify critical components in products and systems, based on the frequency, relevance and observability of their failure modes. Conceived originally in the early 50' for application in electro-mechanical systems design in the field of Military, it has been subsequently extended to general technical systems in the industrial sector (Stamatis, 2003) and even to organizational activities in the civil domain. While the original FMECA formulation explicitly relied on failure rate data in order to compute a criticality number for each component, easier to apply formulations were subsequently developed using combination of numerical scores, such as the one based on the Risk Priority Number (RPN), which has been widely used in the automotive sector. RPN is traditionally computed as RPN = S x O x D, being S, O, D respectively the failure mode Severity, Occurrence and Detectability scores. A general review of FMECA techniques in risk assessment is provided by Liu et al. (2013). Limitations of available FMECA approaches are discussed in the literature (Agarwala, 1990; Bowles, 2003, Caputo, 2005), while examples of alternative and improved formulations are discussed for instance in (Braglia, 2000; Braglia et al., 2003; Franceschini and Galetto, 2001; Liu et al., 2016; Song et al., 2014) as well as in the references cited in such papers. Building on the FMECA conceptual approach, in this paper for each kit component the susceptibility to error commission based on its morphological characteristics and specific requirements will be assessed. Then a risk priority number will be computed based on the error consequences and detectability at the assembly level. This allows to determine critical components based on their properties, and assess the components suitability to kitting. This may lead to kit redesign and improved operational procedures in order to reduce errors occurrence. While in the literature detailed models have been suggested to quantify errors in kitting processes based on human reliability analysis (Caputo et al., 2017), the proposed FMECA-based approach has the advantage of being more practitioner-oriented and amenable to utilization on the shop-floor by assembly and warehouse managers. Moreover, it directly provides a criticality assessment of components. It is also conceptually sound given that a strong analogy holds between failure modes of equipment and human errors in manual procedures. In the paper at first a taxonomy of human errors in kit preparation is discussed. Subsequently, the dedicated FMECA method for kitting processes based on the Risk Priority Number approach is detailed.

2. A taxonomy of kitting errors

A kitting process includes several activities, including pick list preparation from the product bill of materials, parts picking, parts counting or weighing to ensure the right number of parts is included in the kit, parts preparation (i.e. processing, cleaning etc.), part placement into the kit (possibly respecting a proper sequence or positioning the part in a dedicated housing slot), final quality check, compilation of missing parts list, temporary kit storage, delivery to assembly line etc. Most of the kit preparation activities are carried out manually and are error-prone. In the literature some taxonomies of kitting errors have been developed based on either empirical analysis and human error analysis techniques (Caputo et al., 2017; Fager et al., 2014). However, in this work we are only interested in those errors which are related to parts-specific requirements, so that parts characteristics uniquely determine the parts criticality as far as kitting errors are related. Therefore, this work builds on the available taxonomies but restricts the scope of the analysis only to errors made during the kit preparation tasks, thus ignoring errors in kit distribution or in pick lists preparation. Moreover, we only consider errors which can be attributable to specific parts features. Errors common to all parts, and independent from individual parts features, such as forgetting to pick a part or to insert a picked part into a kit, or omitting a generic final quality check, are neglected because they affect in the same manner all parts type and do not determine a specific criticality of a part.

With the previous caveat, for our purposes the processes to be carried out when kitting a part only include the following task, i.e. part picking, part processing (optional), parts counting (optional), part placement in dedicated position within the kit (optional), part checking. In case one or more of the above operations is affected by an error, the consequence will be the occurrence of some Logistic Error (LE), i.e. I) Part missing from kit; II) Wrong part in kit; III) Part unfit for use/damaged; IV) Incorrect parts number (in case of multiple parts); V) Parts in wrong sequence/position.

However, such LEs can be determined by several distinct types of human errors.Given that many different human error classification schemes exist in the literature, the error categories proposed by Swain and Guttman (1983; Schuller et al., 1997) have been chosen, including Omission, Commission, Selection, Sequence, Timing (i.e too early, too late) and Quantity (i.e. too much, too few) errors. By matching the above LEs classes with Swain and Guttman's categories of human errors one obtains the taxonomy shown in Table 1. Occurrence of human errors listed in Table 1 can be associated to parts-specific requirement and used to assess the part criticality as far as the kitting process is concerned. Occurrence of parts non-conformity may determine assembly errors and end product non-conformity.

Table 1: Error taxonomy for the kit preparation process

JOB DESCRIPTION	ERROR CATEGORY						LOGISTIC ERRORS
Task	Omission	Commission	Selection	Sequence	Timing	Quantity	
Part picking			a				I); II)
Part processing (optional)	b	c; d					III)
Part counting (optional)	e					f	IV)
Part placement in kit				g			V)
Part checking	i	h					I); II) III) IV) V)

LEGEND - HUMAN ERRORS: a) Failure to identify correct part; b) Processing not performed; c) Incorrect processing; d) Unwanted processing (part damaged); e) Counting not performed; f) Counting error; g) Placement in bad position; h) Wrong check performed; i) Quality control omitted.

Kitting errors have a chance of being detected and corrected before final assembly or at an end-of line error correction station. This incurs an error correction cost. In case errors are not corrected non-conforming products are delivered to customers determining product non-compliance or failure with corresponding liability and economic loss.

Based on the taxonomy of Table 1 the following error types may be associated to each distinct specific requirement or feature of a part.

EA) Part identification error. The part needs to be correctly identified because it can be confused with a similar part, otherwise the wrong part type may be inserted in the kit.

- EA1) the kitting operator fails to properly identify the part type based on its distinguishing features and picks a similar but incorrect part. This error type corresponds to error a) in Table 1.

EB) Part processing error. The part is susceptible to damage from incorrect processing (including handling). As a consequence the part inserted into the kit is damaged and unfit for intended use. This happens because

- EB1) the operator forgets to process the part. This error type corresponds to error b) in Table 1.
- EB2) the kitting operator causes a damage during part handling. This error type corresponds to error d) in Table 1.
- EB3) the kitting operator commits an error when processing the part (i.e. cutting to length, cleaning etc.).This error type corresponds to error c) in Table 1.

EC) Part placement error. This happens where the part requires an exact placement within the kit.

- EC1) The right part has been inserted in the wrong place within the kit or in the wrong sequential order. This error type corresponds to error g) in Table 1.

ED) Counting error. In case of parts having a prescribed multiplicity (higher than one) the wrong number of items is included in the kit. This happens because:

- ED1) the operator forgets to count parts. This error type corresponds to error e) in Table 1.
- ED2) the operator fails when counting the parts number. This error type corresponds to error f) in Table 1.

EE) Quality check error. The final check on the part fails. The operator has an opportunity to check that the part has been correctly included in the kit. However, this final formal check may fail because:

- EE1) the operator forgets to perform the final quality check. This also includes the operator forgets to verify the integrity of the picked part in case it is susceptible to damage (this should be intended as a conditional probability, i.e. the probability that the integrity is not verified at the picking time provided that the part was already damaged). In fact, susceptibility to damage is a specific feature of a part. This error type corresponds to error i) in Table 1.
- EE2) the operator performs the check but fails to identify and correct the possible non-conformity on the checked part. This error type corresponds to error h) in Table 1.

Overall, the association of parts specific requirements to applicable human errors is resumed in Table 2.

Table 2: Parts requirements

Requirement	Error type
Requires identification respect similar parts	EA1
Susceptible to damage	EB2, EE1
Requires processing	EB1, EB3
Requires a specific positioning within kit	EC1
Requires counting	ED1, ED2
Requires a final quality check	EE1, EE2

3. The KEMCA model

In this section the Kitting Error Modes and Criticality Assessment (KEMCA) model is described. According to the FMECA/RPN approach we assume that the criticality assessment should be individually performed for each part to be inserted into a kit taking into account

1. probability/frequency of error commission, expressed by score O (= Occurrence);
2. the magnitude of errors consequences, expressed by score S (= Severity);
3. the error detectability and the possibility of applying risk mitigation measures (i.e. means to avoid error occurrence), expressed by score D (= Detectability).

The above scores are used to compute a Part Criticality Number (PCN). However, in this work, according to (Caputo, 2005) we use a modified additive approach for PCN computation, as shown in Eq. (1), which ensures the avoidance of typical pitfalls of traditional RPN formulation, such as scenarios ranking duplication, and reduces sensitivity to small changes of the parameters values.

$$RPN = (S + O)\,D \tag{1}$$

The logic behind Eq. 1 is that both S and O concur to assess the risk associated to an error mode, while term D refers to the risk mitigation capability and could apply to both S and O contributions, even if in the specific case of kitting risk mitigation could be mainly pursued in a preventive manner, i.e. reducing error occurrence. Scores S, O, D are given as described in the following.

3.1 Assignment of Severity score

The severity score S assesses the magnitude of consequences of a non-conformity in the examined part. We assume that the consequence of a part non-conformity, regardless of the type of error causing the non-conformity, affects the quality of the end product and can represent an economic loss, a potential hazard to the user, and a failure of the product to fulfil its intended scope. Let us define S_i as a partial severity score associated to the *i*-th type of consequence, then the overall severity score S is computed as

$$S = \sum_{i=1}^{3} S_i \tag{2}$$

where S_1 is the partial score associated to the economic impact of the error, S_2 is related to the maximum extension of the consequences as far as the system functionality is concerned (i.e. it expresses the extent of system functionality degradation), while S_3 accounts for the severity of possible damage to people and users.

Table 3: S_1 ranking criterion

Relative economic impact CR	S_1 Score
0 – 0.3	0
0.31 – 0.6	1
0.61 – 1 (or higher)	2

S_1 is assigned in the 1 to 3 range as shown in Table 3 according to the value of the Cost Ratio CR

$$CR = \frac{\text{Expected error cost}}{\text{Maximum affordable (or sustainable) cost}} \tag{3}$$

which assesses the relative economic impact of the failure. In this case the expected error cost may be the internal error correction cost or an external error correction cost. The former is the cost borne to pick a new part in the warehouse to substitute the defective/wrong one provided that the error has been discovered before assembling the product, or is the end-of-line part substitution cost if the non-conformity is discovered after the assembly is completed but before the product sale. According to Caputo et alt. (2017) correcting a detected kitting errors before part assembly implies a unit cost CDKE (€/error),

$$CDKE = \left(T_p + \frac{2d_{avg}}{v_{tp}} \right) C_{oh} \tag{4}$$

while end-of-line correction of of undetected kitter's or assembler's errors incurs the unit cost CRQ (€/error)

$$CRQ = CDKE + (T_d + T_i + T_a)\, C_{oh} \tag{5}$$

being T_p (h) the time to pick the replacement component in the kitting area, d_{avg} the average distance between the kitting area and workstations, v_{tp} the walking velocity of the operator or the speed of the material handling vehicle, C_{oh} (€/h) the operator's hourly cost, T_d (h) the time to disassemble the end product to replace a component, T_i (h) the inspection time needed to identify the component to be replaced, T_a (h) the time to reassemble the end item. Instead an external correction cost is incurred when the error is not detected at the assembly plant and determines an equipment malfunction and a customer complaint or legal liability. This determines an economic loss including cost to return and substitute the defective product, loss of customer's goodwill, contractual penalties for selling a non-conforming product etc. The external cost and the order of magnitude of maximum affordable cost is determined by the company on a case-specific basis.

Score S_2 is assigned in the 1 to 4 range following the indications of Table 4.

Score S_3, representing injury or fatality, is computed as

$$S_3 = K(1 + \beta) \tag{6}$$

where the basic score K is assigned as described in Table 5 in the 0 to 2 range, while β is a multiplier coefficient referring to the extension of the damage as far as the number of affected people is concerned. Coefficient $\beta = 0$ in case a single individual can be affected while $\beta = 1$ in case multiple individuals can be affected. This allows to assign a higher weight to damage to personnel, in that the K score may be increased up to a factor of 2.

Table 4: S_2 ranking criterion

Failure effects extension	Score
Failure remains confined to the examined system level or extends to higher levels but without compromising the functionality of the system.	0
Loss of formal conformity without compromising performances	1
Failure extends to levels higher than the one examined reducing the performances of the system.	2
The failure compromises the primary function of the system.	3
The failure effect extends beyond the system boundary and affects the surrounding environment.	4

Table 5: S_3 ranking criterion

Damage to people	K Score
No damage	0
Injury	1
Permanent damage or death	2

3.2 Assignment of Occurrence score

More than one error can be associated to a part (the maximum number of possible errors is 9, see Table 2), and the part is non-conforming provided that at least one error occurs. Therefore, we assume that the occurrence score O is proportional to the number and types of possible errors affecting the part and their individual probability of error occurrence. The higher is the number of potential errors, and the higher the probability of occurrence of the errors, the higher is the occurrence score. In order to compute the occurrence score, at first all potential errors associated to the part should be identified. This is carried out referring to the specific requirements of the examined part, according to the error list of Table 2. A frequency of occurrence class is then associated to each applicable error according to Table 6. Please note that a part identification error (EA1) is a consequence of the failure to identify the distinguishing features of the part. Typical identification features are shape, color or identification code, symmetry or other geometrical features. Therefore, a part can have more than one identifiable features. The higher the number of available distinguishing features, the lower is the probability of failing to correctly identifying the part. In fact, in that case picking the wrong part requires the occurrence of multiple simultaneous features identification errors. Therefore, in case a part has only one distinguishing feature the probability class is assigned as High, while in case of two or more features the assigned probability class is Low. Classes indicated in Table 6 are assigned on the basis of actual human errors probability detailed elsewhere (Caputo et al., 2017). After assigning each error its corresponding probability class, the highest obtained probability class of the applicable errors is denoted as the Dominant Probability Class (DPC) and is associated to the part. The occurrence score is then assigned on the basis of the number of applicable errors and the part probability class according to Table 7.

Table 6: Errors probability of occurrence class

Error type	Probability class
EB1, EA1*	Low (≈ 10^{-4} errors/occurrence)
EB2, EB3, EC1, ED1, EE1, EE2	Medium (≈ 10^{-3} errors/occurrence)
ED2, EA1*	High (≈ 10^{-2} errors/occurrence)

* Class depends from number of distinguishing features (see text for explanation).

In practice, by examining a part one determines the applicable requirements (i.e. the part needs to be counted, can be confused with similar parts and needs positive identification, must be placed in a precise position within the kit etc.). Based the applicable requirements one determines the corresponding error types by inspecting Table 2. By inspecting Table 6 one determines the highest probability class of the applicable errors, which becomes the part DPC. Based on the part DPC and the overall number of applicable errors one assigns the occurrence score by inspecting Table 7. For sake of example, let us consider a part which requires identification on the basis of two distinct features, requires counting because more than one units need to be inserted into the kit, requires specific placement within the kit. According to Table 2 the applicable errors are EA1, ED1, ED2, EC1. EA1 is assigned probability class Low because there are two separate identifiable features, while ED1 and EC1 are assigned probability class Medium, and error ED2 is assigned probability class High (see Table 6). The highest obtained probability class is High, which becomes the DPC assigned to the part. In correspondence of DPC = High and four applicable errors Table 7 assigns an occurrence score O=8. As an alternative, a quicker method to assign the occurrence score is given in Appendix I.

Table 7: Occurrence score assignment Table.

	Number of applicable errors								
Dominant Probabilty Class	1	2	3	4	5	6	7	8	9
High	7	8	8	8	9	9	10	10	10
Medium	4	4	5	5	6	6	6	7	7
Low	1	1	1	1	2	2	3	3	3

3.3 Assignment of Detectability score

The detectability score depends on the possibility of detecting the occurred error, with the implicit assumption that once an error is detected it is possible to correct it and avoid the consequences. Therefore, it also represents the concept of avoidability, i.e. the applicability of possible preventive measures avoiding the error occurrence. In case a preventive or corrective measure can be enforced the effectiveness of a potential error is thus reduced or even eliminated. In fact, no consequence or loss could happen in case all errors could be prevented or discovered. In this respect, parameter D acts as a measure of preventability of the errors consequence.

While the identification of possible errors-avoidance measures is outside the scope of this work, it can be suggested that such measures include improved training of kitting operators in order to better distinguish from similar parts, use of check lists, warning messages in the pick list to signal the presence of critical parts, introducing Poka-Yoke solutions when designing kit containers, adding distinguishing features (i.e. colour coding, shape modifications etc.) to easily confused parts. In order to implement the above logic we at first compute a Residual Equivalent Error Number (*REEN*) for the part

$$REEN = \sum_{i=1}^{N} \frac{E_i}{EDP_i} \qquad (7)$$

where N is the total number of applicable errors (max $N = 9$), $E_i = 0$ in case the i-th error occurrence can be eliminated by adopting a proper preventive measure or $E_i = 1$ in case the error occurrence is not preventable, while EDP_i is the Error Detection Probability of i-th error. *EDP* score is assigned as follows: 1 = difficult to detect; 2 = fairly easily detectable; 3 = easy to detect. Then *D* score is assigned according to Table 8.

Table 8: D score assignment rule

REEN	*D* score
≤1	0.5
1≤*REEN*≤3	0.75
≥ 3	1

3.4 Criticality assessment

Once scores *S*, *O*, *D* are computed according to the above described procedure, the criticality of the part is assessed by computing its criticality number PCN using Eq. (1). According to the described procedure the PCN rating can vary in the 1 to 20 range, and three broad criticality ranges may be identified as shown in Table 9. Logistic managers can thus concentrate their efforts on components identified as critical parts, in order to improve the effectiveness of the kitting process by adopting proper and case-specific redesign, training and error avoidance strategies.

Table 9: Criticality classes

PCN range	**Criticality evaluation**
1 to 5	Errors are unlikely or can be easily detected and corrected. There is no relevant risk either from the economic point of view and under the user's health perspective. The part is not critical from a kitting perspective.
6 to 12	Errors are probable, with not negligible internal cost and possibility of consequences extending at the system level and impacting on the user. Possibility of compromising product quality in the eye of the user. The part needs attention

	from a kitting process perspective.
13 to 20	Errors are frequent, with possibility of relevant economic loss and consequences extending beyond the system boundaries. Risk to the user including harm is possible. The part is critical from a kitting perspective.

4 Conclusion

In this paper a method to rank parts criticality in kitting processes has been proposed. The method takes into consideration the specific error-prone requirements of individual parts and is based on a modified FMECA/RPN approach. While the method is fairly detailed, in that it takes into account the different human errors applicable , the preventability of such errors and different kinds of consequences, it also appears enough easy to use to be quickly applicable in the operational environment of the shop floor of an assembly department. In future research the method will be practically applied in several industrial case studies in order to verify its effectiveness and to devise proper error avoidance strategies useful to improve parts and kit design and operational procedures.

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APPENDIX I

In case a quicker method is preferred to compute the occurrence score, the following Table can be used. The user selects the proper partial score for each of the nine potential error types, from EA1 to EE2 according to the Table. Partial scores are then summed to obtain the occurrence score O, and the total, when not integer, is rounded to the next integer.

Error type	Error code	Description	Suggested score	Chosen score
Identification error	EA1	Part can not be confused	0	
		Part can be confused but has several distinctive features	0.2	
		Part can be confused but has one distinctive features	1	
		Part can be confused and has no (or hardly identifiable) distinctive features	2	
Processing error	EB1	Part does not require processing	0	
		Part requires processing	1	
	EB2	Part can not be damaged during handling	0	
		It is difficult to damage the part during handling	0.2	
		The part can be easily damaged during handling	1	
	EB3	Part does not require processing	0	
		Part requires processing	1	
Placement error	EC1	No specific placement	0	
		Specific placement is required but housing slot can not be confused	1	
		Specific placement is required and housing slot can be confused	2	
Counting error	ED1	Part does not have to be counted	0	
		Part has to be counted	0.5	
	ED2	Part multiplicity =1	0	
		Part multiplicity ≤8	1	
		Part multiplicity ≤8	1.5	
Quality check error	EE1	Part does not require any check or part can not be damaged	0	
		Part requires a check, including possible part damage needs to be checked at time of picking	0.5	
	EE2	Part does not require any check	0	
		Part requires a check	0.5	