Control strategies comparison for a multi-stage assembly system using simulation

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Abstract: The goal of Zero Defect Manufacturing (ZDM) is to reduce part scrap by compensating manufacturing deviations and avoiding their propagation on multi-stage production systems. In particular, the joint use of in-process measuring and flexible locating systems enables the application of different control strategies to proactively improve the geometrical quality of the product and to achieve the productivity targets. In this work, focused on the production quality paradigm, two compensation strategies based on the adjustment of part locators are simulated to compare how different control loops can reduce the out-of-control parts in multi-stage assembly systems. For this purpose, a simulation tool developed on OpenModelica is used taking into account the logistic flow and the quality characteristics flow based on the Stream of Variation model.

Keywords: Production quality, Multi-stage assembly systems, Stream of variation, Simulation, Control strategies.

1. Introduction
Manufacturing companies operating in highly competitive markets are constantly challenged to design and exploit production processes and systems to improve key factors such as productivity and product quality, for example by reducing wastes associated with low exploitation of resources or scrap for products that do not meet the required quality. In this context, the production quality paradigm arises to combine the disciplines of production, quality and maintenance [1]. The main goal of the production quality paradigm is to keep under control and improve over time the production rate and the level of compliant parts with minimal waste of resources and materials. The production quality paradigm is aligned with the zero-defect manufacturing (ZDM) approach whose objective is the defect removal in manufactured products [2], but this goal is more difficult to achieve when manufacturing systems become more complex, as in the case of multi-stage assembly systems in which quality defects are propagated throughout the different stages.

Traditional SPC techniques treat the multi-stage system as a whole and lack the capacity to discriminate among changes at different stages. However, modern manufacturing systems integrate, in addition to inspection stations to control the final quality of the products, other sensors and automated tools, which allow the use of active control strategies to reduce or avoid quality defects. In the assembly system context, different control strategies for improving quality have been proposed such as the selective assembly, in which the parts to assembly are classified and selected, or the locators adjusting strategy as proposed in the trimming technique [3]. The last control strategy introduces corrections on
the fixture locators based on the data provided by the sensors and inspection stations for compensating defects and their propagation in the manufacturing stages.

However, the complexity of multi-stage manufacturing systems requires the use of analysis techniques for assessing the impact of the different control strategies and logics on the productivity and the quality indicators of the system. For this type of analysis, the use of multi-domain simulation models at different stages of the life cycle of the system is essential. These simulation models are fundamental for: a) the Digital Twin both in the first stages of design and commissioning of the system; b) virtual test and evaluation of the solutions adopted; c) improvement of reactive and proactive capacities during the production stage. Moreover, these simulation models should include the integration of system behaviours in different domains. Nowadays, this integration is eased through the development and use of co-simulation models and tools. Modelica [4] is an equation-based, object-oriented behavioural simulation language that has been shown to be a suitable language to take into account geometrical and multi-physical constraints at the conceptual design phase. However, after an extensive bibliographic review, a lack of research oriented towards the development of frameworks for the management of geometric variations has been detected, especially in modelling and simulating the effects of geometric variations for quality assurance, productivity and their interrelations [3].

Aware of the importance of multi-domain and multi-scale simulation in both design and operation of new manufacturing systems, our research group has focused its activity on the design and implementation of a multi-scale simulation platform to evaluate and control productivity and geometric quality variability in multi-stage manufacturing systems [5]. One of the first remarkable results in this research was the definition of a simulation metamodel that enables the co-simulation of the flow of materials (logistic flow) and the flow of the product quality characteristics in an integrated way. This metamodel is founded on the discrete events simulation (DEVS) formalism, for modelling the discrete dynamic behaviour of manufacturing processes, and the stream of variation (SoV) technique for modelling the propagation of geometric quality deviations at each process stage [6].

This paper presents the application of a multi-domain simulation during the design stage of a multi-stage assembly line to carry out a comparative study of the indicators (productivity and quality) using an automated trimming control [3] with different logics. More specifically, special attention will be paid to the response of each alternative to an out-of-control state caused by the geometric quality of input material. Specifically, the case study analyses the welding assembly process of a product made up of three parts, and it is focused on the comparison of different control logics to adjust fixture locators in order to compensate the geometric errors from the incorporated parts and improve the key quality characteristics of the final product.

The following sections present the experimental procedure adopted (section 2) and the analysis of the main results obtained in the simulations (section 3). Finally, the main conclusions of the work are commented.

2. Experimental procedure
The development of this comparative study is based on a methodology that makes use of a previous metamodel as a fundamental tool and follows a procedure consisting of 4 steps, which will be discussed below. In section 2.1, the co-simulation metamodel used to create executable models is presented. The steps of the procedure are commented below, first defining the objective of the study (section 2.2). Later, the conditions of the case study are established, specifying the product, the process and the production system (section 2.3). Finally, after planning the experiments and implementing the executable simulation models for each defined case (section 2.4), the results of the experiments are analysed (section 3).

2.1. Main tool: the co-simulation metamodel
This study is based on the use of the multi-domain simulation metamodel for the analysis of geometric variability and productivity in multi-stage assembly systems presented in [5]. This metamodel was initially developed in SysML and later mapped to Modelica for exploiting its co-simulation capabilities.
integrating different domains. The metamodel includes the structural elements necessary for the definition of the simulation models for multi-stage assembly systems. Two types of elements can be highlighted: those that model the behaviour of workstations and those that support the application of different control logics. These metamodel elements were implemented using the OpenModelica tool by defining some Modelica libraries. Later, using these libraries, executable simulation models were defined, implemented, and executed in the OpenModelica environment.

The metamodel elements that model the behaviour of the workstations are based on the DEVS formalism to support the discrete flow of materials (logistic flow) over the processes, and consider assembly stations with measurement capacity, inspection stations, product queues stores and part suppliers among others. On the other hand, the modelling of the geometric quality deviations and their propagation is based on the SoV technique [6], whose fundamental expressions are defined as:

\[
X_k = A_k \cdot X_{k-1} + B_k \cdot U_k + W_k 
\]

\[
Y_k = C_k \cdot X_k + V_k
\]

The \(X_k\) vectors quantify the geometric quality deviations of each part, after the assembly stage \(k\). The \(U_k\) vector represents the deviations introduced by the fixture at the positioning points in the stage \(k\). \(A_k\) and \(B_k\) are the transformation matrices that propagate the geometric quality deviations and they are built from the nominal geometry of parts and the assembly process plan. Specifically, \(A_k\) introduces the effect of the geometric deviations of input parts and \(B_k\) introduces the effect of locating points deviations in part positioning. The matrix \(W_k\) introduces the effect of additional deviations due to a random noise of zero mean. In equation (2), \(Y_k\) is the vector of the measured deviations values obtained in the measurement process at stage \(k\). These points are defined by the product features and they correspond to the product key quality characteristics. The values of the measured characteristics \((Y_k)\) are the result of the part geometry (matrix \(C_k\)) and the uncertainty of the measurement process introduced with the matrix \(V_k\).

Moreover, the metamodel also supports various control logics based on a compensation strategy, which consists of a final inspection station to accept or reject the final product combined with the use of fixture locators that allow the introduction of corrections in their position to compensate geometric deviations of the input parts. The corrections in the \(U_k\) values are calculated to minimize the \(Y_k\) values in the final inspection stage. This minimization is computed by applying least squares technique to equations (1) and (2) annulling the values of \(Y_k\). Therefore, the difference between the control logics resides in the way to get the \(X_k\) values, as it is shown in the next section.

2.2. Study goals

As mentioned in the introduction, this paper presents a comparative study of the influence of different control logics in a multi-stage assembly system. More specifically, the study is focused on improving the response in quality terms when an out-of-control arises due to defects in the geometric quality of input material. To achieve this, a control strategy is proposed based on the use of automated locators that allow corrections in their position to compensate geometric deviations of the input parts. Based on this control strategy, two alternative control logics are proposed in [5] and we briefly present them below:

- **Feed-Backward (FB) control logic.** In this type of control, the locators’ corrections are calculated from the geometric deviations of a sample of part measured at the final inspection station. These corrections are calculated for all workstations and they are kept constant until the next sample is inspected. In this control, it is essential to choose properly the sample size and its frequency. As it can be seen, this control logic uses historical data of finished products to adjust and improve the quality of the products to be manufactured.

- **Feed-Forward (FF) control logic** [7]. In this type of control, the locators’ corrections for an assembly station are calculated particularly for each product based on the quality characteristics of the incoming parts. For an assembly station \(k\), these quality characteristics are obtained from
previous measurement operations, which can be obtained in two ways: post-process measurements in stage \( k-1 \) or pre-process measurements in station \( k \). Unlike the FB control logic, this logic can provide good results for each individual product, but it also involves an increase in the processing time due to the measurement and setup operations required for each part.

To address the comparative analysis, different Key Performance Indicators (KPIs) will be considered in order to take into account both productivity (e.g., production rate) and quality (e.g., defect ratio) perspectives, as well as the overall behaviour of the system according to the production quality paradigm (e.g., overall equipment effectiveness).

2.3. Case Study

The case study is based on one of the cases proposed in [5], focused on the welding assembly process of a car side frame. This product is made up of 3 parts: fender, side ring and rear quarter, as shown in figure 1(a). The problem was originally raised as an example of SoV applied on assembly processes to study the propagation of geometric variability. This work takes it as a reference, using the geometric and process plan data.

![Figure 1. (a) Product, parts and location points. Adaptation of [5]. (b) Detail of the location points of Part 1.](image)

The case is a two-dimensional problem in which each part or subassembly is positioned by two locators: a 4-way (circular hole) and a 2-way (slotted hole), as exemplified in figure 1(b). Moreover, the product key quality characteristics are a set of eight product characteristic points identified on its features with a tolerance that limits the maximum admissible deviation to accept the product.

![Figure 2. Process diagram.](image)

The multi-stage production line designed for the assembly and inspection of the product is composed of two assembly workstations and a final inspection workstation, as illustrated in figure 2. To regulate the flow of materials and improve the behaviour when disruptions appear (equipment failures, ...), on each workstation there are queues, in which incoming parts are stored before the processing (assembly,
inspection) machine. There are not outcoming queues at the workstations, so they are blocked if the queue for the next stage is full. For the case study, all queues have capacity for 10 units. Each assembly and inspection operation has an automated fixture for positioning the locating points of the input parts.

The operation of each workstation can include an additional setup activity for the automatic adjustment of the fixture location points that is executed before the assembly or inspection operation. Additionally, each assembly operation may have two measurement activities: a pre-process measurement to know the geometric deviations of incoming parts; and a post-process measurement to know the geometric deviations of the resulting assembly. In this case study, the process times for these activities at each station are distributed according to a normal function whose average times are shown in table 1. For the sake of simplicity, the transport time between workstations has not been considered in the analysis.

Table 1. Average times for each type of activity based on historical data.

| Time                  | Station 1 | Station 2 | Station 3 |
|-----------------------|-----------|-----------|-----------|
| Pre-process measurement | 25 s      | 25 s      | -         |
| Setup                 | 60 s      | 60 s      | 60 s      |
| Process (assembly/inspection) | 240 s     | 300 s     | 110 s     |
| Post-process measurement | 40 s      | 40 s      | -         |

Additionally, the following parameters that have a direct relationship with the SoV formulation (equations (1) and (2)) are defined for the case study:

- Initial quality characteristics of the parts (Xo). The position deviations of the features of each part have been modelled in the two directions of analysis through a normal distribution, with a zero mean value and a standard deviation of 0.05 mm. A mean change of 0.3 mm will be introduced at certain point in the simulation to study the behaviour of the system in response to an out-of-control in the quality of the input parts.
- Quality characteristics related to fixture locators (U). Position deviation of locators have been modelled by a normal distribution of zero mean and a standard deviation of 0.02 mm.
- Uncertainties in measurement and inspection operations (V). The uncertainty has been modelled using normal distributions of zero mean and a standard deviation that depends on the type of station. Specifically, for the measurements in the assembly stations (pre-process and post-process measurements) a standard deviation of 0.03 mm (uncertainty ± 0.09 mm) has been considered. For the inspection station, a standard deviation of 0.01 mm (uncertainty ± 0.03 mm) is defined.
- Maximum allowable tolerance for final assembly acceptance. The tolerance is set to ±0.35 mm in both directions for the position of all features.

2.4. Simulation model implementation and planning of the experiments

An executable simulation model for each scenario was defined in OpenModelica using the blocks of the simulation metamodel libraries. All these simulation models share a common basic structure represented in figure 3, in which it is necessary to replace the Monitor&Control block that supports the calculation of the corrections according to the control logic considered in each scenario.

To address the comparative study, a set of simulations was planned to assess the response of different control alternatives to an out-of-control in the input parts. All the simulations consider initial conditions in the input parts that result in an in-control process. Subsequently, to compare the responsiveness of the control logics, an out-of-control in the position deviations of the input parts is introduced. With these conditions, 3 scenarios were established, giving rise to a total of 4 cases that are specified below:

- Scenario 0: No corrective action is applied. It will be studied in case 1.
Scenario 1: Corrective actions are applied in all stages based on an FB control logic. To assess the effect of sample size and sample spacing, two alternative cases are planned:

- A sample size of 3 products for every 10 finished products (case 2).
- A sample size of 9 products for every 30 finished products (case 3).

Scenario 2: Corrective actions are applied in stages 2 and 3 based on an FF control logic, performing post-process measurements in station 1 and pre-process measurements in station 2 (case 4).

Figure 4 graphically represents the operations and information flows involved in each control logic. To compare the results of the different cases presented, some data was collected from simulations to calculate the following indices: the mean and standard deviation of the quality characteristics of the finished products; the production rate (products/hour); the effective production rate (accepted products/hour); and the defect rate (rejected products/finished products - %).

3. Results and discussion

Once the executable simulation model for each case has been implemented, each experiment is run for a period of 500,000 seconds. During the simulation, an out-of-control in the geometric deviations of the
input parts is introduced at the instant 250,000 seconds in order to analyse the performance of each control logic. Therefore, the behaviour of the system clearly shows two different zones related to initial conditions and out-of-control conditions, as shown in Figure 5. The following results from the perspective of quality and productivity were obtained after running the simulations in all scenarios.

The first result analysed is the maximum geometric deviation of the final products obtained in the final inspection. Figure 5 shows the temporal evolution of the average maximum geometric deviation (computed using the last 10 finished products) comparing the scenarios (figure 5(a)) and the two alternatives in the FB control (figure 5(b)). A transition period is clearly recognizable when the out-of-control is introduced.

![Figure 5](image-url)

**Figure 5.** Average of the maximum deviation in the inspection stage. (a) Comparison of strategies (case 1, 3 and 4). (b) Comparison of alternatives in the FB control (case 2 and 3).

As it can be seen in the initial zone, the comparison of the different scenarios shows similar results (figure 5(a)), except for the control logics applied in case 2, where the maximum deviation increases even under initial conditions when the process is capable. When the out-of-control phenomenon arises, all control logics improve the result in a different way, as commented below.

More specifically, comparing the two FB control alternatives (case 2 and case 3), one can see the dependence of FB control logic with the spacing between part samples and its relation with the work in process (WIP). In case 2, the WIP is near to the spacing between samples, so the samples are not representative of the studied conditions and the results get worse. It is a clear example of over control correction. If the spacing between samples is tuned, as in case 3, the achieved results are improved.

For a quantitative analysis, Table 2 collects the mean value and the standard deviation of the maximum deviation at out-of-control conditions, and the percentage improvement of each control alternative with respect to case 1. Data show that, when the FF logic is applied, the improvement in the mean (36.9%) is surpassed by those obtained with the FB logic with an adequate selection of the sample (60.3% in case 3). The same effect can be observed in the improvement of standard deviations.

| Case | Mean | Mean improv. | Standard deviation | Std. deviation improv. |
|------|------|--------------|--------------------|-----------------------|
| 1    | 0.492| -            | 0.182              | -                     |
| 2    | 0.284| 42.3%        | 0.110              | 39.4%                 |
| 3    | **0.195** | **60.3%** | **0.076** | **58.5%** |
| 4    | 0.310| 36.9%        | 0.108              | 40.4%                 |

Focusing on the results for the defect rate with out-of-control conditions (yellow bars in figure 6), in case 1 the system cannot react to the out-of-control event, generating a 100% defect rate. The FF control
logic shows a reaction which improves the defect rate (27.6%) significantly, but the value is still excessive since, in this case, the corrections introduced from stage 2 cannot compensate the deviations introduced in stage 1. The best reaction to the out-of-control has been observed with the application of the FB logic in case 3, obtaining a 0.8% defect rate.

On the other hand, comparing the production rates (blue bars in figure 6), it is observed that the introduction of the FB control logic does not diminish significantly the production rate. This is not the case of the FF control where the production rate value falls significantly due to the additional time for the measurement and setup operations in each product. Finally, a more complete analysis must include quality and productivity aspects using the effective production rate, that is, accepted products per unit of time (grey bars in figure 6). Under this analysis, case 3 shows the best effective production rate (11.47 products per hour), as a result of combining the lowest defect rate and a high productivity rate.

4. Conclusions

This paper highlights the great utility of multi-domain simulation models to analyse the crossed effects in complex systems. The case study presented takes advantage of multi-domain simulations for analysing a multi-stage manufacturing system in the context of Production Quality paradigm, integrating quality and productivity perspectives.

The case study presented allows us to conclude that case 3 (feedback control with a sample of 9 orders every 30) presents the best results, making a combined evaluation of geometric quality and productivity. However, the importance of the correct definition of the sample used has also been shown in this type of logic, especially in the relationship between the sampling frequency and the size of the stores considered. Based on these results, the study of new control logics is proposed as a future line of work, combining FF control with FB-type corrections for stages prior to the measuring station.

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