Controlling Production Variances in Complex Business Processes

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Abstract. Products can consist of many sub-assemblies and small disturbances in the process can lead to larger negative effects downstream. Such variances in production are a challenge from a quality control and operational risk management perspective but also it distorts the assurance processes from an auditing perspective. To control production effectively waste needs to be taken into account in normative models, but this is complicated by cumulative effects. We developed an analytical normative model based on the bill of material, that derives the rejection rates from the underlying processes without direct measurement. The model enables improved analysis and prediction. If the rejection rate is not taken into account the function of the bill of material as a reference model deteriorates and therefore output measures become more opaque and harder to verify. As a consequence it is extremely difficult or even impossible to assess efficiency and effectiveness of operations. Secondly it is impossible to judge whether net salable assets represent the correct amount and finally it is impossible to assert whether the operations do comply to company standards and applicable laws.

1 Introduction

Technological advances have enabled more and more sophisticated production processes. This leads to a vision of smart manufacturing: "fully-integrated, collaborative manufacturing systems that respond in real time to meet changing demands and conditions in the factory, in the supply network, and in customer needs" [8,17]. However, the flexibility allowed by smart manufacturing, also leads to challenges for quality control and operational risk management. Products can consist of many sub-assemblies and small disturbances in the process can lead to larger negative effects downstream. Such variances in production processes are a challenge from a control perspective. Here control can be understood in the sense of feedback and feed forward mechanisms for optimizing the production process [10], but also in the sense of management control [14] or internal control [5]. All types of control and assurance processes require reliable predictions and a reliable information systems of what actually happened to support management

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decisions about production planning, budget, resource allocation and so on, but also to ensure compliance with laws and regulations. In order to assess whether objectives are met, a *reference model* is needed, that generates a set of criteria to test evidence against [4,22]. In case of manufacturing, such a reference model is based on the way engineers have designed the product and therefore the production process. So the reference model can be depicted as known numerical ratios between different parts of an enterprise's value creation process. Hence by design input and output of resources, equipment and finished products are related by certain specific ratios, depending on the construction of an end-product. Typically, such ratios appear in the Bill of Material (BoM). In accounting theory, such ratios are used to cross-verify accuracy and completeness of reporting [19]. It needs no elaboration that similar equations are used in materials resource planning to control the production process, for planning and scheduling, and for ordering resources [11]. To manage the production process we look at the production volumes using the BoM. The BoM takes a central position in the relationship between volumes and cost. It can be used to decompose products into atomic units and conversely to accumulate quantities from basic units to composite products. Although the BoM is static, it must somehow be reflected in the production process that transforms the parts into the end product.

In this paper we develop a method to specify an analytic normative model of a production process, based on the BoM to relate the volume of end products with the total production volume. The BoM contains all the necessary information to calculate the volume ratios for different products flowing through a process without looking at the actual process details. The computations are an adaptation of Leontief's input output models. Leontief matrices were originally developed to model the input and output of different sectors on a macro economic scale [20]. These models were later extended with parameters for waste and used to indirectly measure how wasteful various parts of the economy were [1,12]. This idea of measuring indirectly is the basis for the computations in this paper, but applied to production processes. Besides the application to input output models, Leontief matrices are also useful for the netting problem in production planning. In this case the bill of material is used to relate input and output volumes of business processes [9]. The computations are similar, but now in a micro economic setting. Given the BoM and the actual volumes we extend the model to calculate the rejection rate. The rejection percentage per product or part gives a fair view of the quantity of waste. In cases the rejection rate is not taken into account, the expected waste is hard to predict because of the cumulative effect. In this circumstance the function of the BoM as a reference model deteriorates. Calculations become more opaque and harder to verify. As a consequence it is impossible to assess efficiency and effectiveness of operations, it is impossible to judge whether net salable assets represent the correct amount and finally it is impossible to assert whether the operations do comply to company standards and applicable laws.

This research makes a scientific contribution to literature about smart manufacturing [8] and use of ICT in production processes [13], but also to literature about computational auditing techniques [16]. Especially we concentrate on a specific measurement problem which has important implications in designing performance management systems.

The outline of the paper is as follows. In Sect. 2 we discuss the role of reference models and motivate why they are needed. In Sect. 3 we provide in an illustrative case: production of integrated circuits which serves as a running example to enhance comprehensibility. In Sect. 4 we start with the nature of a BoM and how the exploded BoM is used from a normative setting to calculate the component variances. In Sects. 5 and 6 we extend the BoM computations with rejection and provide in detail how a BoM can be represented and how waste can be accounted for. In Sects. 7 and 8 we discuss the results applicable in control settings and end up with some conclusions.

2 Reference Models

When data are being processed and used by people for decision making or control purposes, the reliability of the data (accuracy and completeness) becomes a necessary condition [21]. Information integrity concerns the *representational faithfulness* of the information relative to the condition or subject matter being represented [2]. Representational faithfulness involves both accuracy and completeness and therefore timeliness too, as well as the validity with respect to applicable rules and regulations [2]. Reliability and integrity are closely related to information quality in general: reliability buttresses relevance and usability of information. In other words the presented information is bound to be less relevant or usable, when it cannot be relied upon.

Designing reliable information systems is crucial for many stakeholders. For example, business controllers need detailed information to judge whether business operations are efficient and effective. Financial accountants are concerned whether the general ledger is complete and faithfully represents the financial outcomes of business transactions. Internal auditors monitor the effectiveness of the internal controls, to ensure (1) effectiveness and efficiency of operations, (2) reliability of financial reporting, and (3) compliance with applicable laws and regulations [6,7]. Thus, information systems have several functions. They may help to (i) collect and analyze evidence in order to monitor, detect and correct undesired behavior, and (ii) to facilitate the organization to be 'in control' by preventing undesired behavior. Both these functions rely on formal models of the processes and procedures. Business controllers, financial accountants and internal auditors share a common problem. To judge the outcomes of business transactions from an operational, financial or compliance point of view, requires a reference model to assess any flaws in the inter- and intra-organizational workflows. For instance, in case participants do not comply with company standards, additional control measures like rewards and punishment should be put in place [15,18]. However, production processes may lead to production variances that are difficult to control.

Reference models must therefore be able to handle the production variances to preserve predictability – representational faithfulness – and ensure usability for decision purposes. In general, production variances play a central role for material resource planning and control purposes [11]. The financial department is interested in the production variances to determine the actual losses on production and determine the net salable assets. Internal and external auditors use the variance analysis to determine the audit approach and the audit techniques to gather assertion based audit evidence in audit engagements like financial statement audits. It needs no elaboration that for production processes such analysis can become very difficult.

3 Motivating Case

An example of a production process with varying material usage is the production of Integrated Circuits (IC). To produce integrated circuits, assembly companies need to accurately deal with information flow through wafer delivery, receiving, storage, wafer receiving, packaging, testing, finishing, and shipping in order to fulfill customer demand. This means that companies need to integrate various kinds of internal and external data by means of ICT in order to improve productivity [13].

The production of an integrated circuit transforms silicon and various other materials into an integrated circuit. The first step is to produce wafers from silicon. Wafers are discs of silicon on which various layers of other materials are placed. These layers make up the logical circuits. Many identical circuits are printed and later the wafer is cut into dies. Each die is placed in a case and connected with wires to pins. The following table gives some hypothetical material usage in a finished IC. In this case 200 dies are cut from a single wafer.

Product	Material
IC	Die, Case, Wire 0.8 mg
Die	Wafer 1/200
Wafer	Silicon 10 g, Metal 0.12 g

Suppose management is faced with varying cost of materials for production runs with similar production volumes. How can such varying costs be controlled? Since total cost does not provide much information, management could look at production numbers. For example after production of 50,000 ICs and 400 wafers in two subsequent runs the following total production numbers are reported.

Product	Volume I	Volume II
IC	53800.0	53700.0
Die	125900.0	82000.0
Case	53900.0	54000.0
Wafer	1460.0	1150.0
Wire	43700.0 mg	43600.0 mg
Silicon	14700.0 g	11600.0 g
Metal	176.0 g	139.0 g

From a business control perspective these numbers are quite challenging. In the case we compare the outputs from the two subsequent production batches we expect that the used materials and components measured show some logical pattern. How do we judge the extreme upsweep in the used Die, Wafer and Silicon compared to 100 used IC's. In the next section we introduce the BoM as a means for judgement.

4 The Bill of Material

The bill of material (BoM) serves as a reference for product data and contains a list of the parts or components that are required to build a product [11]. A BoM is a multi-level document that provides build data for multiple sub-assemblies (products within products) and includes for each item: part number, approved manufacturers list (AML), mechanical characteristics and a whole range of component descriptors. In some cases the BoM may also include attached reference files, such as part specifications, CAD files and schematics. Managing a production process is equivalent to managing the BoM, in order to track product changes and maintain an accurate list of required components at a certain phase in the production process.

For this paper the most important information in a product's BoM is the parts from which it is composed and in what amount. A product can be atomic, meaning it has no parts, or it can be composed from other products. The amount is needed because the same type of part may be used more than once. If parts can be arbitrarily divided, for example in the case of liquids, the amount need not be restricted to integers.

The BoM for a given collection of products specify a numerical relation among those products. For two products it tells how much of one product is used in the composition of the other. For computational purposes the relation formed by the bills of material is written as a matrix, say matrix B with

$$B_{i,j} = \text{"The amount of product } i \text{ that is used by product } j.\text{"}$$

Each column j in this B-matrix contains the amounts from the bill of material of the j-th product. In the remainder of the paper the distinction between the individual bills and the matrix is not made and the term *bill of material* or abbreviation *bom* is used to refer to the entire collection.

The IC example of the previous section gives the following BoM matrix:

$$B = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.005 & 0 & 0 & 0 & 0 & 0 \\ 0.800 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 10.000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.120 & 0 & 0 & 0 \end{pmatrix}$$

The rows and columns are indexed by the products {IC, Die, Case, Wafer, Wire, Silicon, Metal} in that order.

A BoM can be 'exploded' to handle its recursive structure. For any vector x containing some product volume, multiplication $B \cdot x$ is the volume of all parts from which the products are directly composed. We could compute $B \cdot B \cdot x$ to obtain the volume at the next level and if we continue this indefinitely and add all results we obtain the volume of all direct and indirect parts. An elegant solution from operations research uses the mathematical fact that $I+B+B^2+B^3+\cdot$ equals $(I-B)^{-1}$, which is the generalization of identity $(\Sigma i : 0 \leq i : a^i) = (1-a)^{-1}$ for the geometric series for scalars [9,20]. Define function Υ.

$$\Upsilon(B) = \sum_{0 \leq n} B^n = (I-B)^{-1}$$

Matrix $\Upsilon(B)$ is called the exploded BoM and can be used to compute total volume from output volume.

Example. With the exploded BoM the total production volume can be computed from the output volume

$$\begin{aligned} ideal &= \Upsilon(B) \cdot output \\ &= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0.005 & 0.005 & 0 & 1 & 0 & 0 & 0 \\ 0.800 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0.050 & 0.050 & 0 & 10.000 & 0 & 1 & 0 \\ 0.001 & 0.001 & 0 & 0.120 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 50000.0 \\ 0 \\ 0 \\ 400.0 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 50000.0 \\ 50000.0 \\ 50000.0 \\ 650.0 \\ 40000.0 \\ 6500.0 \\ 78.0 \end{pmatrix} \end{aligned}$$

These numbers specify the ideal volume to produce 50,000 ICs and the 400 wafers. Often these are the products that end up in the end product, but as in the case for wafers it can also be an intermediate product.

Waste corresponds to the produced items that do not end up in an end product. Knowing the ideal parts we can compute it by subtracting that from the total volume. The waste in the running example is

$$waste = totvol - ideal = \begin{pmatrix} 53800.0 \\ 125900.0 \\ 53900.0 \\ 1460.0 \\ 43700.0 \\ 14700.0 \\ 176.0 \end{pmatrix} - \begin{pmatrix} 50000.0 \\ 50000.0 \\ 50000.0 \\ 650.0 \\ 40000.0 \\ 6500.0 \\ 78.0 \end{pmatrix} = \begin{pmatrix} 3800.0 \\ 75900.0 \\ 3900.0 \\ 810.0 \\ 3700.0 \\ 8200.0 \\ 98.0 \end{pmatrix}$$

Vector *totvol* is the reported total volume given in the case description.

Dividing the waste by the total volume gives waste fraction

Product	Waste I	Waste II
IC	7.1%	6.9%
Die	60.3%	39.0%
Case	7.2%	7.4%
Wafer	55.5%	43.5%
Wire	8.5%	8.3%
Silicon	55.8%	44.0%
Metal	55.7%	43.9%

The exploded BoM surely helps to analyse from a normative stance to analyse the extreme upsweep in the used Die, Wafer and Silicon compared to 100 used IC's as identified in Sect. 3. There is one problem we have to address. A BoM models an ideal world. In reality however production plans do address the possibility that components and half fabricates get rejected due to norm deviations. Consequently the above waste calculations I and II are smudged by the components and half fabricates that get rejected. The waste calculations suffer from what we coin the cumulative effect caused by this type of measurement error. So instead of modelling waste we have to model rejections. This can be done by extending the exploded BoM with a reject vector as we will see in the next section.

5 Modeling Rejection Computationally

The computation from the previous section requires the output and the production volume to be specified as vectors. Total production is denoted by *totvol*:

$$totvol_i = \text{“The total production volume of the i-th product.”}$$

and vector *output* is the volume of end-products:

$$output_i = \text{“The end-product volume of the i-th product.”}$$

Whether a product is an end product or not is a property of physical products, not of abstract products. A subset of an abstract product's instances might be used as end products, while the rest is used as part in other products. Since every produced end product must have been processed, inequality $output \leq totvol$ must always hold. For products with end products only this turns into equality.

To model waste and rejection the characteristic recursive equation of the exploded bill of material is extended with a reject vector. Equation

$$totvol = \Upsilon(B) \cdot output \tag{1}$$

from the previous section is a solution to recursive equation

$$totvol = output \ + \ B \cdot totvol \tag{2}$$

This recursive equation expresses the nesting in the products' bills of material. Instead of working with rejection, it is mathematically more convenient to work with the fraction of products that is accepted:

$$\begin{aligned} \alpha_i &= \text{"the fraction of product } i'\text{s volume that is accepted."} \\ &= 1 - \text{"the fraction of product } i'\text{s volume that is rejected."} \end{aligned}$$

The basic equation that relates the quantities from the introduction is

$$\alpha \times totvol = output \ + \ B \cdot totvol \tag{3}$$

Everything in the remainder of this paper is derived from this equation. Before explaining it, the term $B \cdot totvol$ is examined first.

Value $B \cdot totvol$ is the key to the recursion in the equation. Earlier we saw the $B.x$ is the volume of all parts from which the products are directly composed, but now we are interested in special case $B \cdot totvol$. Since $totvol$ is the total flow $B \cdot totvol$ contains each end product's direct parts but also the parts at deeper levels of composition, but in ideal amounts. The amounts have to be corrected for rejected parts. So the interpretation of $B \cdot totvol$ is that it is the volume of all non rejected parts flowing through the process.

Continuing from the interpretation of $B \cdot totvol$ of the previous paragraph we derive that since *output* is the ideal end-product volume that the sum of *output* and $B \cdot totvol$ must equal the total ideal flow. Another expression for the total ideal flow is $\alpha \times totvol$. Putting both expressions together gives the equation.

The hardest problem is to calculate *totvol* given *output* and α. If *totvol* and *output* are given we can directly calculate α by rewriting the equation to

$$\alpha = (output \ + \ B \cdot totvol) \ / \ totvol$$

Calculation *output* from *totvol* and α is done by rewriting the equation to

$$output = \alpha \times totvol \ - \ B \cdot totvol$$

For real physical production processes this result cannot contain negative numbers. The next section deals with the solution if *output* and α are known. First we give an example computing α.

Example. Given the bill of material from the previous example and the following volumes we can calculate α. Compute

$$\alpha = \frac{output \; + \; B \cdot totvol}{totvol}$$

$$= \frac{\begin{pmatrix} 50000.0 \\ 0 \\ 0 \\ 400.0 \\ 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 & 0 & 0\,0\,0 \\ 1 & 0 & 0 & 0 & 0\,0\,0 \\ 1 & 0 & 0 & 0 & 0\,0\,0 \\ 0 & 0.005 & 0 & 0 & 0\,0\,0 \\ 0.800 & 0 & 0 & 0 & 0\,0\,0 \\ 0 & 0 & 0 & 10.000 & 0\,0\,0 \\ 0 & 0 & 0 & 0.120 & 0\,0\,0 \end{pmatrix} \cdot \begin{pmatrix} 53800.0 \\ 125900.0 \\ 53900.0 \\ 1460.0 \\ 43700.0 \\ 14700.0 \\ 176.0 \end{pmatrix}}{\begin{pmatrix} 53800.0 \\ 125900.0 \\ 53900.0 \\ 1460.0 \\ 43700.0 \\ 14700.0 \\ 176.0 \end{pmatrix}}$$

$$= \begin{pmatrix} 0.9294 \\ 0.4273 \\ 0.9981 \\ 0.7051 \\ 0.9849 \\ 0.9932 \\ 0.9955 \end{pmatrix}$$

Now we have the actual reject. For comparison the waste table is repeated.

Product	Waste I	Waste II	Reject I	Reject II
IC	7.06%	6.89%	7.06%	6.89%
Die	60.29%	39.02%	57.27%	34.51%
Case	7.24%	7.41%	0.19%	0.56%
Wafer	55.48%	43.48%	29.49%	29.57%
Wire	8.47%	8.26%	1.51%	1.47%
Silicon	55.78%	43.97%	0.68%	0.86%
Metal	55.68%	43.88%	0.45%	0.72%

We think it needs no elaboration that introducing the reject vector extending the exploded BoM model was very effective. Comparing the results waste versus reject it becomes clear that Cases, Wire, Silicon and Metal waste is mostly caused by cumulative effects. Hence the Reject is measured indirectly so we are still not sure whether our calculations give a good picture to judge production outputs. As we will show in the next section we can model reject directly instead of indirectly. We expect to obtain the insightful results.

6 Using Rejection as Norm

Instead of computing the rejection from the waste, we can also use rejection as norm and compute normative production volumes and waste from it. Rejection can be used as norm by reversing the usage of the equation.

The central equation is conveniently solved with the aid of adjusted bill of material B/α. Matrix B/α is defined by

$$(B/\alpha)_{i,j} = B_{i,j} \;/\; \alpha_i$$

Matrix B's i-th row is scaled by the i-th factor from α. The result is that a matrix multiplication followed by a compensation for waste is combined into a single operation. It is easy to show that

$$(B/\alpha) \cdot x = (B \cdot x) \;/\; \alpha \tag{4}$$

Product $B \cdot x$ measures the usage of the product and dividing by α compensates for waste. We now can state a non-recursive equation for *totvol*. Applying it to the result of above derivation we get:

$$totvol \;=\; output/\alpha \;+\; (B/\alpha) \cdot totvol \tag{5}$$

Exploding then gives

$$totvol = \Upsilon(B/\alpha) \;\cdot\; (output/\alpha) \tag{6}$$

Vector $output/\alpha$ is the number of end-products adjusted for waste. Now we can calculate

$$\begin{aligned} totvol &= \Upsilon(B/\alpha) \;\cdot\; (output/\alpha) \\ &= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2.222 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0.016 & 0.007 & 0 & 1 & 0 & 0 & 0 \\ 0.800 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0.162 & 0.073 & 0 & 10.204 & 0 & 1 & 0 \\ 0.002 & 0.001 & 0 & 0.120 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 52631.6 \\ 0 \\ 0 \\ 571.4 \\ 0 \\ 0 \\ 0 \end{pmatrix} \\ &= \begin{pmatrix} 53800.0 \\ 125900.0 \\ 53900.0 \\ 1460.0 \\ 43700.0 \\ 14700.0 \\ 176.0 \end{pmatrix} \end{aligned}$$

So to produce the 50,000 ICs and 400 wafers we expect these numbers of products to flow through the process.

From the planned production we can also compute planned waste. First we determine planned waste given the normative reject fractions used earlier. The second table is the same planned waste, except the reject of the die is lowered from 55% to 35%. This causes a cumulative effect on wafers, silicon and metal of more than 10%.

Product	Reject I	Reject II	Waste I	Waste II
IC	5.00%	5.00%	5.00%	5.00%
Die	55.00%	35.00%	57.25%	38.25%
Case	0%	0%	5.00%	5.00%
Wafer	30.00%	30.00%	53.80%	43.47%
Wire	0%	0%	5.00%	5.00%
Silicon	2.00%	2.00%	54.72%	44.60%
Metal	0%	0%	53.80%	43.47%

The results are clear. By using rejection as norm and compute normative production volumes and waste from it gives us the precise insights. The calculations show that a product's waste may vary considerably, even when its reject does not vary.

7 Application in Control Environments

The example illustrates how only a little disturbance in the rejection rate will cause considerable effects in the assembly line of integrated circuits. Therefore it is more convenient to take rejection into account in reference models and derive waste from it. This can be done by extending the exploded BoM by a so called accept vector, which is defined as the fraction of product volume that is not rejected. Given the BoM and the actual volumes we can calculate the rejection rate. The rejection percentage per product or part gives a fair view of the quantity of waste.

Being in control starts with the key question: "can we judge production volumes and compare the results". We would like to defend that in general production volumes are difficult to judge without knowing the relationship between volumes of different products as we have seen in Sect. 3. The BoM gives a controller and managers insights in the normative relationships. Sure they should be reflected in the process, but misses process efficiency and occupancy rate norms. This is what we have seen in the end of Sect. 4. Without these norms the cumulative effect will give difficult to control varying numbers. As we have demonstrated process efficiency norms can be computed from ideal BoM and overall numbers. Needless to say that these numbers should correspond to the actual process and are additionally very useful for benchmarks, cross-checking and reconsolidation controls.

The implication is that we can infer that the information based on the exploded BoM extended with the reject vector is consistent so that differences between reject percentages actually inform us about the efficiency and effectiveness of the assembly processes. Waste suffers from cumulative effects which gives us the wrong information so that it is impossible to verify the actual outcome in terms of rational expectations and costing behavior. Any procedure to assess waste without the reject vector is bound to be an illusion.

In that case also the costing behavior will be harder to predict and it will be harder to judge whether generated volumes correspond to predicted volumes, to find out whether records are represented faithfully. Indeed the hidden error would influence inventory levels and therefore affect procurement decisions. We expect that the return on investment will be negatively influenced by hidden errors caused by the cumulative effect. But there is another catch. In case the rejection rate is not taken into account, the expected waste is hard to predict. In this circumstance the function of the BoM as a reference model deteriorates. Calculations become more opaque and harder to verify. As a consequence it is impossible to assess efficiency and effectiveness of operations, it is impossible to judge whether net salable assets represent the correct amount and finally it is impossible to assert whether the operations do comply to company standards and applicable laws.

8 Conclusion

In this paper we have addressed the verification problem required by management, quality managers, and financial accountants or imposed by legal authorities. Verification of the accuracy and completeness of records, as guaranteed by a system of internal controls, requires a reference model. However, such models usually do not account for waste or losses. The issue was how to control the production variability in production processes.

A sound way to do this is to use the bill of material (BoM). The BoM takes a central position in the relation between volumes and cost. The BoM contains the information to calculate the volume ratios for different products flowing through a process. This can be quite difficult, because of the recursive nature of the calculations required for material handling, warehousing or procurement purposes. Using the BoM we do not need detailed registrations for every task executed in the processes to determine reject ratios.

In this paper we show how to define the relation between end products, waste, and components by a recursive matrix equation, that is based on the BoM. By exploding the BoM the ideal ratios can be calculated and compared with the actual outcome of the production process.

Auditors or financial controllers make use of so called audit equations, that capture the numerical ratios between the parts used in a value creation process [3]. Any waste disturbs the equations and consequently needs to be taken into account. Here we show, that in order to do predict the total volume of waste, it is enough to estimate the rejection rate, for each end-product or intermediate product. This research makes a scientific contribution to literature about smart manufacturing [8] and the use of ICT and data in production processes [13], but also contributes to the literature about computational auditing techniques [16]. In addition, it has practical value, for all those professionals who need a reference model to verify reports against, such as process controllers, as well as internal and external auditors. They need to account for waste too.

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