A Cost Model for SMARTLAM

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***Abstract*—In this paper, we present a cost model for the production of small and medium batch series based on the SMARTLAM 3D-Integration approach, which allows fast prototyping without the normally neccessary allocation of tools. To accomplish this task, we use the concept of *total value*, which also includes the benefit. Because the majority of costs in SMARTLAM are caused by manufacturing overhead costs, we use an overhead calculation based on the machine-hour rate. Our model includes production cost calculation for the different used modules (i.e., Excimer- and CO_2 laser, aerosol-jet 3D printer, laminator, micro-assembly module) as well as for the coordination module and the whole manufactoring plant.**

Keywords*–micro-systems; additive manufacturing equipment; cost model.

I. Introduction

SMARTLAM (Smart production of Microsystems based on Laminated Polymer Films) is a project funded by the European Commission, with the goal to develop and integrate a complete set of micro technology based fabrication modules into a full production line without the normally required allocation and or modification of tools, masks, and hardware adaptations [1]. The aim is to develop a highly flexible and reconfigurable hot pluggable production unit which allows for the production of smaller lot sizes even down to customized tailored parts with lot size down to one part. With this approach a fast and flexible prototyping can be realized, but also competitive production of individual items or small batch series and mass customisation was in the scope of this project. The SMARTLAM 3D-Integration approach (3D-I) combines new material properties with state of the art, scalable 3D technologies such as aerosol jet printing, laser based micro structuring, laser welding, processes for combined micro milling, surface functionalisation, micro welding, and micro cutting [2]. Important questions in this context are how to calculate the costs of a micro technical component and if the production costs are competitive compared to established production methods. The SMARTLAM production cell is illustrated in Figure 1.

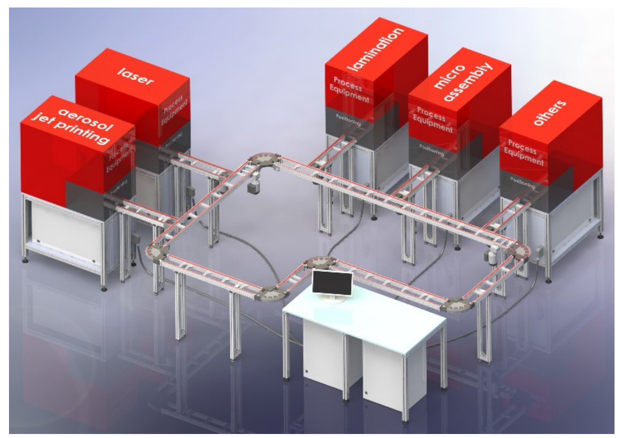

Figure 1. Simulation of SMARTLAM Production cell

To answer these questions, the SMARTLAM production system will be analyzed and evaluated with the methods of cost accounting. The paper is structured as follows: In Section II, we present the different costs, which must be considered in our model. The main ideas of this paper are presented in Section III, where we develop the actual cost model. Starting with generic costs and the costs of the different modules (Excimer-Laser, CO_2-Laser, Aerosol-Jet 3-D printer, Laminator, and Micro-assembly) we develop the cost function of the overall process. Further, the paper will finish with a short conclusion in Section IV.

II. Cost Concepts

A. Cost concept of total value

The literature embraces different definitions of cost concepts: the *cash-based* cost concept and the concept of *total value* [3], [4]. The concept of *total value* differs in the valuation of the consumption of goods compared to the first concept. The *total value* approach uses the final utility for evaluation; the *cash-based* concept uses the actual value on the buying market.

This paper establishes a cost model of the manufacturing process. The cost concept of *total value* is used in this paper to identify the costs, because it includes the benefits. In the following, all types of costs in SMARTLAM will be specified.

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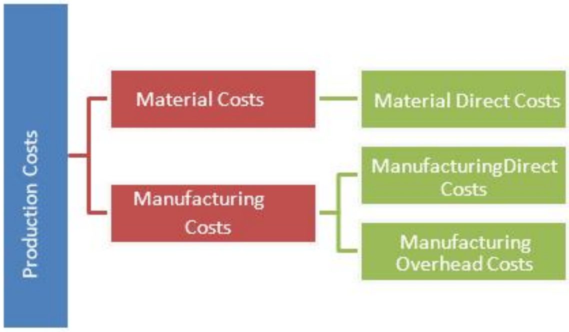

Figure 2. Types of costs for the production costs accountable in SMARTLAM (from [5])

B. Production Costs

The consideration of the production costs is the essential basis of the carried out analyses. This is why in the following, this specific cost structure is addressed in detail. The production costs accrue during fabrication. There are differences between costs for the material (material costs) and arising costs during manufacturing a product.

Figure 2 shows a simplified presentation of the approach of Walter and Wünsche [3], since the material overhead costs and extra production direct costs were not considered. The production costs in SMARTLAM are divided into material and manufacturing costs, the latter further differed in direct and overhead costs. Direct costs will be assigned directly to a product or cost centre, overhead costs are assigned indirectly, as these costs are caused by several products or cost centres. The material overhead cost consists mainly of procurement of the material and administrative costs for this material. As this work considers only costs generated during production, these costs are not taken into account. For the evaluation of the manufacturing process in SMARTLAM, only the material direct costs and the attributable manufacturing direct and overhead costs are relevant.

In the following, these types of costs are explained in detail.

- Material direct costs: The direct costs of material are valued on basis of the value on the buying market.
- Manufacturing direct costs: These costs occur during the production and can directly be ascribed to a product.
- Manufacturing overhead costs: The majority of costs in SMARTLAM fall into this category. The overhead costs occur for several products and are spread prorated between the products. Following costs are assigned to this category especially for SMARTLAM:
    - Wage costs
    - Costs for supplies
    - Energy costs
    - Depreciation costs
    - Interest charges
    - Costs for operating materials

The following section describes the method for spreading the overhead costs.

C. Production Costs

1) Overhead calculation: In addition to the direct costs there are overhead costs of the production. To get these costs split in a correct way among the products, the overhead calculation method is used. In the following, this method will be described in detail.

There are several overhead rates to characterize the overhead costs:

- Material overhead
- Manufacturing overhead
- Administration costs
- Selling expenses

For this paper, only the manufacturing costs are relevant, because these are the only ones who are collected in the production costs.

The SMARTLAM process provides a high flexibility and a module-based design, which makes machine-hour rate calculations the most suitable solution for SAMRTLAM. In the following, the method of machine-hour rate calculation will be explained in detail.

2) Machine-hour rate calculation: Due to high automation and new, flexible manufacturing plants the wages in production decreased significantely, followed by an increase in the manufacturing overheads (e.g., plant construction and controlling). The limits of the overhead calculation method are reached with products using the manufacturing plant in different ways and time, because the overhead rates depend mainly on the wages, which are not proportional to the production time.

Non machine-dependent overhead costs are not considered in this method and will be allocated to the direct costs via overhead calculation [4]. The SMARTLAM production has different products and a very flexible production planning, which allows to split the overhead costs precisely to each product depending on their production time.

The following calculation model in (1) is used for the machine-hours [3]):

$$machine\_hour\_rate(MHR) = \frac{machine\_overhead}{machine\_runtime} \quad (1)$$

To calculate the machine hour rate (MHR), the machine-dependent overhead costs should be determined very precisely. The following list displays the necessary parameters for calculation the MHR [4]:

- Machine replacement value (C_{repl})
- Useful life of machine in years (t_{life})
- Interest rate for replacement value (I)
- Repair and maintenance costs of machine per year (C_{maint})
- Work center costs of machine per year (C_{space})
- Fixed auxiliary material of machine per year (energy) (C_{fix})
- Variable auxiliary material of machine per year (energy) (C_{var})

The MHR for the manufacturing plant is calculated in the following way (2):

$$MHS = \frac{\frac{C_{repl}}{t_{life}} + C_{repl} * I + C_{maint} + C_{space} + C_{fix} + C_{var}}{t_{machine\_runtime}} \quad (2)$$

The methods of overhead calculation on basis of machine-hour rate calculation are suitable for the modelling of the manufacturing costs calculation above, because the overhead costs of the manufacturing plant can be registered through the production time which complements perfectly the flexible manufacturing process of SMARTLAM.

A calculation model for the manufacturing costs is sought, which shows the cost structures of the process and enables the calculation of the accumulating costs.

III. Elaboration of the SMARTLAM Cost Model

This section shows the development of a model to identify and calculate the manufacturing costs of the production with the SMARTLAM 3D-I process.

A. Generic costs

1) Overhead costs of the SMARTLAM production: In this section, all overhead costs of the manufacturing plant will be defined, i.e., all costs, which can be attributed to each product or are produced on the SMARTLAM plant. The production plant works autonomous most of the time; there is only one worker per shift necessary for operating of the facility. This worker refills the material (production raw material, auxiliary supplies, working supplies), modifies the plant between products, reacts to errors and picks up completed products and stores them in the warehouse.

The wages of the worker will be allocated on the products with the wages-rate. This value is calculated by (3):

$$wages\_rate(C_{wages}) = \frac{Wages}{machine\_running\_time} \quad (3)$$

The wage of one worker is about 80,000 €per year and the machine running time is 2,000 hours per year (assumption: work to capacity). This leads to a wage rate (C_{wages}) of 0.67 €/min. (4).

$$C_{wages} = \frac{80,000}{2,000 * 60} \text{ €}/min = 0.67 \text{ €}/min. \quad (4)$$

The wages are charged to the product costs via their operating time on the manufacturing plant. This is done with the time the product is processed on the plant, multiplied with the wages-rate. Within the product cost calculation, these generic costs are added to the caused costs of a module. In the following, the unconsidered manufacturing plant-related costs will be discussed.

2) Collective plant costs: Besides the modules for each technology, the manufacturing plant also owns a material-flow system, which connects the modules and a collective control computer for the complete plant. This computer optimizes the production flow and coordinates the modules. As these parts are working with each module, the costs are allocated equally to each module. On basis of the machine-minute-rate (C_M) and the process time (t_{pi}) the variable machine overhead costs can be charged. In Table 1, all costs of the manufacturing plant are listed [6]. These costs can be allocated to each module.

TABLE I. OVERHEAD COSTS OF THE COLLECTIVE MANUFACTURING PLANT OF SMARTLAM

Types of cost	Variable	Value
Replacement value of the machine	C_{repl}	65,000 €
Useful life of the machine	t_{life}	5 years
Interest rate of the replacement value	I	5%
Work centre costs of the machine	C_{wrk}	$25m^2 * 72$ €$/m^2$ $= 1,800$ €
Variable auxiliary material (energy)	C_{var}	5 €/hour

These costs accrue annually for the use of the machine and are calculated with an operating time of 2,000 hours per year. The model displayed in (5) is used to calculate the machine-hour-rate (MHR):

$$MHR = \frac{\frac{C_{repl}}{t_{life}} + \frac{C_{repl}*I}{2} + C_{wrk} + C_{var}}{t_{running}} \quad (5)$$

With the values of Table I, the MHR can be calculated with 13.23 € per machine-hour.

The production time in SMARTLAM is measured in minutes, therefore the machine-hour-rate is converted to the machine-minute-rate (C_M) with the value 0.22 €per production minute.

By adding up the wages costs (4), the overhead per minute raises to the value of 0.89 €.

B. Functions for the production cost of the modules

The SMARTLAM 3D-I process enables a flexible production of several products with different specifications. Due to the modular concept of the manufacturing plant it is possible to reorganize the modules for each product. This makes it more difficult to calculate the production costs, because on one hand the calculation model has to be flexible and generic. On the other hand the model must fit all production processes. Variables, which stay unchanged for each product, will already be valued in the generic model with values of the production.

The rejects, the products with defects from the production, are separately considered for each module. In the microsystem technology it is called Yield (Y) matches the yield in percent (%) of the final products [7].

The production costs per film (C_{sheet}) of a process step, divided by the yield results in the total production costs (C_{total}) and reject costs (C_y) are shown in (6):

$$C_{total} = \frac{C_{sheet}}{Y}$$
$$C_y = \frac{C_{total}}{Y} - C_{total} \quad (6)$$

The time of transport between the modules and for configuration of the module is considered in the time t_{tc} and has a fixed value of 30 seconds.

1) Costs of the Excimer Laser module: The Excimer Laser module includes the Excimer Laser technology.

a) Manufacturing overhead costs: The Excimer Laser costs 65,000 € and is the most expensive laser technology of SMARTLAM. Additional costs of 12,000 € incur for the module housing and controlling. The life time is five years. The depreciation costs (C_{Depr}) for this module are calculated as shown in (7):

$$C_{Depr} = \frac{65,000 + 12,000€}{5\ years} = 15,400€/year \tag{7}$$

This yields to depreciation cost ($C_{InvExLas}$) of 0.13 €/min.

The acquisition costs above do not include all costs for optics and lenses, because some objects wear out multiple times a year. Every year there are wear costs of 23,000 € or 0.19 € per minute. Added to the acquisition costs, this results in overhead costs (Cr_{ExLas}) of 0.32 € per minute for the Excimer Laser module.

Several gases and masks are used for laser operations. The costs therefore are collected in the rate C_G for gas (0.03 € per minute) and C_M for the masks.

The overhead costs are allocated to the products using their process time. The time depends on the ablation volume (V) and the speed of the laser (v_{ExLas}), which depends on the material. Added to the time for the transport and changing the worktables (t_{tc}) it results in the formula for the process time (t) as shown in (8):

$$t = \frac{V}{v_{ExLas}} + t_{tc} \tag{8}$$

b) Total cost function for Excimer Laser: Cutting off a lot of material leads to disposal costs (C_d), which must be added to the production cost of the module.

For SMARTLAM there is a yield of 95% for operations with the Excimer Laser. Together with the manufacturing overhead costs it results in the total cost function for calculating the production costs of the Excimer Laser module as shown in (9):

$$C_{ExLas} = \frac{(Cr_{ExLas} + C_M + C_G) * \frac{V}{V_{ExLas}} + t_{tc} + C_d}{Y} \tag{9}$$

2) Costs of the CO_2 Laser module: The CO_2-Laser module includes the CO_2 Laser technology. Compared to the Excimer Laser the acquisition value of the CO_2 Laser of 45,000 € is significantly cheaper and so, the depreciation per year is only 11,400 € ($C_{InvCo_2Las} = 0.10e/min.$).

Costs for Gas (C_G) amounts to 0.01 € per minute and are therefore also cheaper compared to the Excimer Laser.

a) Total cost function for the CO_2 Laser module: The total cost function is similar the Excimer Laser, but there are no costs for masks. The yield is also 95%. Equation 10 shows the formula (with ablation speed v_{co_2Las}, ablation volume V):

$$C_{Co_2Las} = \frac{(C_{InvCo_2Las} + C_G) * (\frac{V}{v_{Co_2Las}} + t_{tc}) + C_d}{Y} \tag{10}$$

3) Costs of the Aerosol-Jet 3D printer module: The Aerosol-Jet 3D printer module includes the Aerosol-Jet 3D printer technology. In the following, the cost model of this module will be defined.

a) Manufacturing overhead costs: The replacement value of this module includes the acquisition costs of the 3D printer and housing costs for the module. The acquisition costs are today 130,000 €, whereas the module costs are 12,000 €. The technology has a normal lifetime of five years, but depending on its operations it can last much longer [8]. The following formula shows the deprecation costs of the Aerosol-Jet 3D printer module.

Depreciation costs per minute are calculated in (11):

$$Depreciation = \frac{130,000\ € + 12,000\ €}{5\ years} = 28,400\ €/year \tag{11}$$

This yields to depreciation costs ($C_{InvAero}$) of 0.24 € per minute.

The process time can be measured based on the ink and the printing speed of the 3D printer. The amount of ink depends on the printing area and how thick the ink should be applied on the material. This can vary depending on the ink and the thermal sensitivity of the material [8].

The following formula shows the calculation of the process time, depending on printing volume V), ink quality k_{ink}, printing speed v_{aero}, and the transport time between the modules t_{tc}.

$$t = \frac{V * k_{ink}}{v_{aero}} + t_{tc} \tag{12}$$

The Aerosol-Jet 3D Printer needs a nitrogen supply. The costs for this gas are displayed in (13):

$$C_{N_2} * t = 0.001\ €/min * t \tag{13}$$

b) Material costs: Material costs for ink (14) include the exercise price multiplied with the printing area and the factor for the application thickness of the ink.

$$C_{ink} * V * k_{ink} \tag{14}$$

The exercise price depends on the raw material costs and the costs for the ink catridge.

c) Total cost function Aerosol-Jet 3D printer: The Aerosol-Jet 3D Printer has a yield of 90% for SMARTLAM. The following formula includes the manufacturing overhead costs and material costs of the printer, together in one total cost function.

$$C_{Aero} = \frac{(C_{InvAero} + C_{N_2}) * (\frac{V * k_{ink}}{V_{Aero}} + t_{tc})}{Y} + \frac{C_{ink} * V * k_{ink}}{Y} \tag{15}$$

4) Costs for the Laminator module: The Laminator module includes the laminating technology. In the following, a cost model for this module will be defined.

a) Manufacturing overhead costs: Compared to the other technologies in SMARTLAM, the laminator ranges in the midfield with a total of 65,000 €. This module is featured with a long life time of 10 years. For calculating the depreciation costs, the costs of housing and controlling of the module should be considered.

$$Depreciation = \frac{65,000\text{ €} + 12,000\text{ €}}{10\ years} = 7,700\text{ €}/year \quad (16)$$

This corresponds to a depreciation value (C_{InvLam}) of 0.06 € per minute.

The overhead costs are allocated to the products throughout their operating time on the laminator module. The process time depends on the material (resistance to heat) and the necessary accuracy. If there is only one layer with functionality, the alignment time of the layers is nearly negligible. If both layers possess functionalities, the alignment is crucial for this process. The process time also depends on the length of the layer and the speed of the laminator. If none of the films has an adhesive layer, additional adhesive has to be applied, which causes further costs of auxiliary material in the amount of $C_{ad} * A_{film}$. After the lamination process the adhesive has to be cured.

$$t = (\frac{L_{film}}{v_{Lam}} + t_{pos} + t_{ad}) + t_{tc} \quad (17)$$

b) Material costs: In most cases, only one layer has functionality. This has the advantage that no exact alignment is necessary for a good quality. The costs of the second film belong to the material costs. If the second layer is also edited, the costs for material are already collected and therefore not listed in the laminator costs.

c) Total cost function for the Laminator module: Equation 18 combines the manufacturing overhead and material costs of the laminator module in one function. Table II shows the used variables.

TABLE II. PARAMETER FOR THE LAMINATING MODULE

Parameter	Meaning
C_{InvLam}	Depreciation costs for the adhesive in $€/min.$
C_{film}	Material costs of the second layer
Y	Yield
C_{ad}	Material costs for the adhesive in €/min.
t	Process time in sec.
v_{lam}	Lamination speed im $mm^2/sec.$
t_{pos}	Positioning of both layers in sec.
t_{ad}	Applying time of the adhesive in sec.
A_{film}	Laminating area in mm^2
L_{film}	Length of film in mm

$$C_{Lam} = \frac{C_{InvLam} * \frac{\frac{L_{film}}{v_{Lam}} + t_{pos} + t_{ad} + t_{tc}}{60}}{Y} + \frac{C_{film} + C_{Ad} * A_{film}}{Y} \quad (18)$$

5) *Costs of the Micro-Assembly module:* Applying adhesive, putting materials (e.g., LED chips) in place or curing of adhesive, as well as curing of the laminated films is done by this technology. In the following, a cost model for this module will be defined.

a) Manufacturing overhead costs: This technology has an acquisition value of 60,000 € and a lifetime of five years. With the costs for housing and controlling of the module (12,000 €) the depreciation costs are calculated

$$Depreciation = \frac{60,000\text{ €} + 12,000\text{ €}}{5\ years} = 14,400\text{ €}/year \quad (19)$$

This yields to depreciation costs (C_{InvMon}) of 0.12 € per minute.

The manufacturing overhead costs are allocated to the products through their process time in the Micro-Assembly module. The time depends on the operation and further on material, adhesive and components. Furthermore factors like precision, thermal sensitivity and number of parts per film are important for calculation. The process time of this module is split into time for adhesive application, positioning of components and curing of adhesive. Necessary time frames are measured individually per part and must therefore be multiplied with the number of parts per film.

$$t = n * (t_{adh} + t_{pos} + t_{cur}) + t_{tc} \quad (20)$$

b) Material costs: There are material costs for adhesive ($C_{MatDis} * V * n$) and components ($C_{MatComp} * n$).

c) Total cost function for the Micro-Assembly Module: Equation 21 shows the manufacturing overhead costs and the material cost combined in one function. The yield of this technology is 99.38%. The used parameters can bee seen in Table III.

TABLE III. PARAMETER FOR THE MICRO ASSEMBLY MODULE

Parameter	Meaning
Y	Yield
C_{InvMon}	Depreciation costs of the module in €/min.
C_{ad}	Material costs for the adhesive in $€/mm^3$
t	Process time in sec.
n	Number of operations in min.
V	Volume of pockests in mm^3
t_{adh}	Time for filling one socket in min.
t_{pos}	Positioning per socket in min.
t_{cur}	Curing time of adhesive per pocket in min.

$$C_{Mon} = \frac{C_{InvMon} * n * (t_{adh} + t_{pos} + t_{cur} + t_{tc})}{Y} + \frac{n * (C_{Ad} * V + C_{MatComp})}{Y} \quad (21)$$

C. Cost function of an overall process

The production cost function of an overall process is put together with the cost functions of the modules. Depending on the process some module are used multiple times, which makes the overall function an accumulation of all cost functions. Costs for transport between the modules and controlling the facility are covered with the time t_{tc}, which is used in every module.

The overhead costs of the manufacturing plant are allocated to the products with their production time on the facility. Normally there are several products on the plant at the same time, which makes the slowest module decisive for the overhead costs of a product.

The following function shows the calculation of the production costs of a film in SMARTLAM (use parameters explained in Table IV):

TABLE IV. PARAMETER FOR THE COST CALCULATION OF THE OVERALL PROCESS

Parameter	Meaning
C_{unit}	Costs per unit
$C_{process}$	Costs of all process steps
C_{Mtotal}	Machine-related overhead costs of a product
C_{pi}	Costs of the process step i
C_{oh}	Overhead cost rate in $€/min.$
$t_{i_{max}}$	Time of the proces step with the longest operation in sec.
n	Number of products on a film

$$C_{Sheet} = C_{Process} + C_{Mtotal} = \sum_{i=1}^{n} Cpi + C_{oh} * \frac{t_{i_{max}}}{60} \quad (22)$$

The production costs per unit results from the division of the production cost of a film by the number of products on the film which are shown in (23).

$$C_{UNIT} = \frac{C_{sheet}}{n_{output}} \quad (23)$$

IV. CONCLUSION

With the generic costs described in Section III-A and the cost functions of the modules described in Section III-B, which are combined in the overall cost function in Section III-C, the calculation of the production costs of any product, manufactured on the SMARTLAM production plant can be done. This model is applicable to any production using these six modules. If more technologies are added to the manufacturing plant the model has to be reworked.

Costs for transport between the modules, inspection and controlling of the plant are detected in the fixed time t_{tc} in every module. Within the implementation of the first production plant new knowledge should replace the fixed time.

If there are new functionalities or an updated technology, the cost function of the modules must be expanded. Each addition can be done in the function of a module and does not change anything on the overall cost function.

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