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Improvement of injection moulding processes by using dual energy signatures

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Abstract

Minimising waste is the credo of all lean production systems. Process steps are therefore divided into value-adding and non value-adding ones. The best practice tool for this purpose is the value stream mapping method (VSM). It reveals waste in inventory and lead time~~s~~. However, if it comes to improve value streams in terms of energy efficiency, then the manufacturing process itself has to be looked at dual, with regard to value-adding and non value-adding elements. This paper presents two methods of dualising the time and energy consumption in the plastic injection moulding process. Potentials for improving the process, from the viewpoints of energy and time, are highlighted. Based on the dual process analysis, improvement concepts are brought forward. The VSM can thus, while maintaining its inner logic, be extended to an energy value stream mapping method (EVSM).

Keywords: Energy efficiency injection moulding; Dual energy signatures; Energy evaluation of production processes; Energy value stream mapping

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1. Introduction

Since 1995, the consumption of plastic materials has risen by more than 250%, and is still growing [1]. Furthermore, new materials and technical improvements enlarge the field of application of this material. Materials such as e.g. glass, metal or paper are substituted more and more frequently. In the processing of plastic materials, injection moulding is the most important process. It is very energy-intensive as it requires energy for melting of the material as well as for cooling the moulded components.

Fossil energy is a limited resource. In combination with the growing energy consumption of the industrialized countries it becomes a more and more important cost factor. The crude oil price, has risen by the factor of 4 over the last decade [2]. For many plastic manufacturer energy becomes an increasingly important cost factor. This requires much more transparency of to the energy consumption of machinery than in the past.

The dual energy signature method is probably be best practice for the identification of waste of time and energy [3, 4]. This method divides the time and energy input dual into value-adding and non value-adding.

In this article the authors present two methods for dualising the time and energy input required in plastic injection moulding. Based on these analyses optimization opportunities are proposed to reduce the energy consumption significantly. Furthermore it is shown the description how VSM is consistently extended to become an EVSM.

2. Injection moulding

2.1. Process description

Plastic injection moulding makes it possible to produce components with complex geometries. According to DIN 24 450 the task of an injection moulding machine (IMM) is to

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discontinually produce moulded components from preferably macromolecular moulding materials [5].

IMMs in general consist of two functional units that are arranged separately: the injection unit and the clamping unit [6] – see fig. 1. The heated plasticising screw is the main item of the injection unit. The clamping unit includes the moulding tool and ensures that the mould is and keeps closed while the plastic is injected. Depending on its drive concept the clamping unit is either force or fitting design.

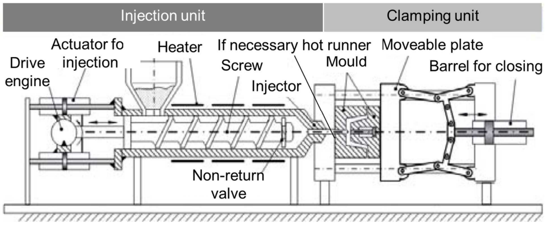


Fig.1. Schematic view of an IMM (according to [6])

IMMs are distinguished by their drive concepts - either with a hydraulic, or an electric or a hybrid drive system. Hydraulically driven IMMs are equipped with a centralised pump system. Electrically operated IMMs use separate servo-electric drives for each movement. Hybrid IMMs combine the two drive technologies.

Fig. 2 shows an injection moulding cycle in principle. The granulate feed to the machine are plasticised in the injection unit (metering phase). The heat required for melting is provided by the rotating plasticising screw in form of frictional heat (approx. 60%) and by the external heating of the barrel (approx. 40%) [7]. After the mould is closed, the plasticised mass is injected into the cavity at high pressure (injection phase). During injection the screw acts as an axially movable piston. Holding pressure phase serves to compensate the material shrinking of the moulded component. The cooling of the part is achieved by a defined heat dissipation in the mould (cooling phase). During the cooling phase the material for the next cycle is metered out. As soon as the surface layer of the injected material has solidified the part can be demoulded. The clamping unit opens and the part is removed from the mould. The cycle has come to an end now and a new one can start.

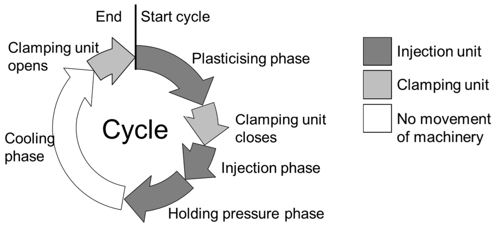


Fig.2. Schematic representation of the process steps in the injection moulding of a component

2.2. *Energy required in principle during the injection moulding of plastics*

Fig. 3 shows the energy requirement in principle of a hydraulically operated IMM during one production cycle. The power consumption and the duration of the process segments will vary depending on the part and the settings.

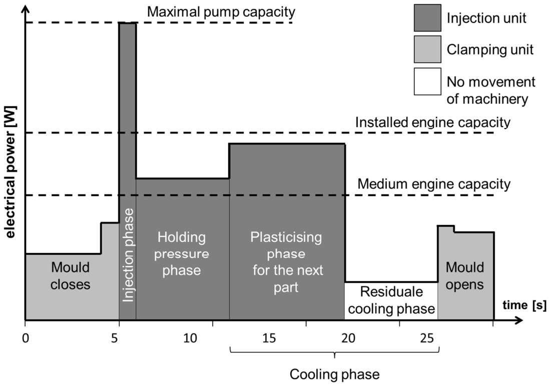


Fig. 3. Basic power requirement of a hydraulic IMM (according to [8])

2.3. *Energy requirement determined in a laboratory test*

In the Aalen University Polymere Processing Laboratory, a moulded component was produced from plastic material polybutylene terephthalate (PBT) on a hydraulically operated IMM (Demag, clamping force 80 t). The component was a box with the measurements 160 mm length x 110 mm width x 60 mm height, and a wall thickness of 4 mm and a weight of 176.4 g – see Fig. 4.

The power curve was recorded using a portable meter brand Yokogawa. Fig. 4 shows the energy consumption of the hydraulic pump (IMM drive), the barrel heater, and the control unit during one cycle.

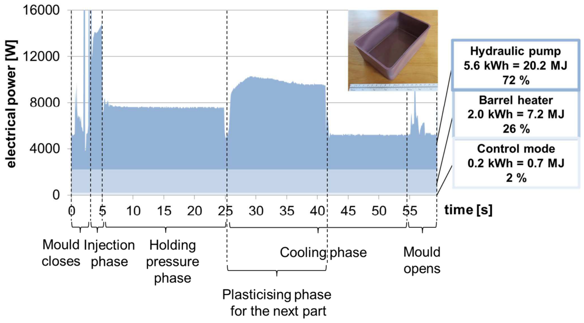


Fig. 4. Power curve in lab test at Aalen University

3. Dual energy signature

An analysing of production processes by means of dual energy and time signatures makes it possible to draw a clear line between value-adding process elements and non value-adding elements, with regard to their duration as well as their energy requirement [3].

To record dual energy signatures in the injection moulding processes the authors suggest the following methods:

- Dual energy signature by ‘air filling’
- Dual energy signature by ‘ideal process’

*3.1. Dual energy signature by '**air filling**'*

The comparison of the power curves recorded in a cycle while processing vs. a cycle without material ('air filling') is one principle of the dual approach. To do this, the settings of the control unit of the machine had to be changed. The process sequences itself remain unchanged.

Fig. 5a, shows the energy consumption during production, i.e. material is injected into the mould. Fig. 5b, shows the energy consumption during 'air filling', i.e. air is injected into the mould instead of material. If both signatures are overlaid one gets the dual energy signature, Fig. 5c, bottom. In this signature the value-adding elements (dark blue) of the process are clearly distinguishable, from the non value-adding elements (light blue) with regard to their duration as well as to the input of energy.

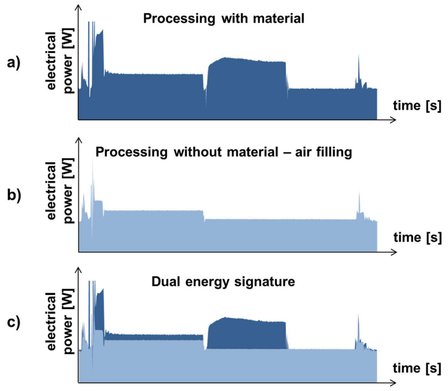
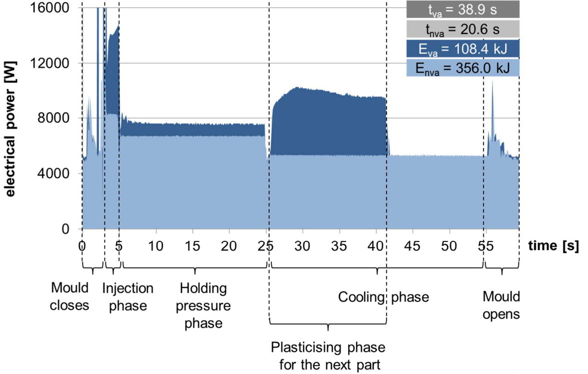


Fig. 5. Energy signature material filling, 'air filling' and representation of the dual energy signature

Details of these analyses are shown in Fig. 6. The light blue signature shows the electrical power consumption during air filling, while the dark blue signature shows the additional power consumption for material plasticising and filling. Only these two process steps are value-adding. The value-adding times are marked by dark grey bars above the signature.



Injection moulding - air filling			
Cycle Time = 59.5 s		Energy Input = 464.1 kJ	
t_{va} = 38.9 s; t_{nva} = 20.6 s η_{tva} = 65 %		E_{va} = 108.1 kJ; E_{nva} = 356.0 kJ η_{Eva} = 23%	
t_{va}	t_{nva}	E_{va}	E_{nva}

Fig. 6. Dual energy signature **air filling**

The value-adding energy (E_{va}) directly required for material plasticising and filling is 108.1 kJ, the value-adding time (t_{va}) needed is 38.9 s in total. The non value-adding input of energy (E_{nva}) is 356.0 kJ, while the non value-adding input of time (t_{nva}) is 20.6 s.

The value-adding efficiency of the process in terms of time, η_{tva}, (equation 1) as well as the value-adding efficiency in terms of energy, η_{Eva}, (equation 2), can now be defined. The results are shown in the data box, see Fig. 6, bottom.

$$\eta_{t_{va}} = \frac{t_{va}}{t_{va} + t_{nva}} = \frac{38.9s}{38.9s + 20.6s} = 65\% \tag{1}$$

$$\eta_{E_{va}} = \frac{E_{va}}{E_{va} + E_{nva}} = \frac{108.1kJ}{108.1kJ + 356.0kJ} = 23\% \tag{2}$$

*3.2. Dual energy signature by '**ideal process**' calculation*

The second method to evaluate the efficiency of the actual process is to assume an idealised production process.

A paper written by the Ilmenau University of Technology and KraussMaffei Technologies GmbH [9] shows how an 'idealised IMM' could be described. 'In a lossless injection moulding process, only the **melting energy** and the **forming energy** are required for producing the moulded component. It is supposed that the machine movements are friction-free and that they therefore do not require any additional energy', … [9]. It is also supposed that no further energy is required to lock the machine and to keep it closed.

- Melting energy

The melting energy can be equated with the enthalpy increase of the plastic material. The value of the specific enthalpy of PBT is 450 J/g, see Fig. 7. The barrel is considered to be fully insulated thermally.

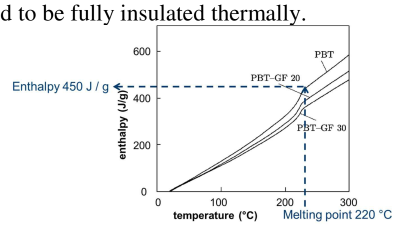


Fig. 7. Determining the melting energy of PBT [10]

The required melting energy is calculated by means of the specific enthalpy and the weight of the moulded component (176.4 g) – see equation 3.

$$\begin{aligned}\text{Specific Enthalpy} &= 450\,\frac{J}{g} * 3600\,s * 176.4\,g \\ &= 22.1\,Wh = 79.6\,kJ\end{aligned} \tag{3}$$

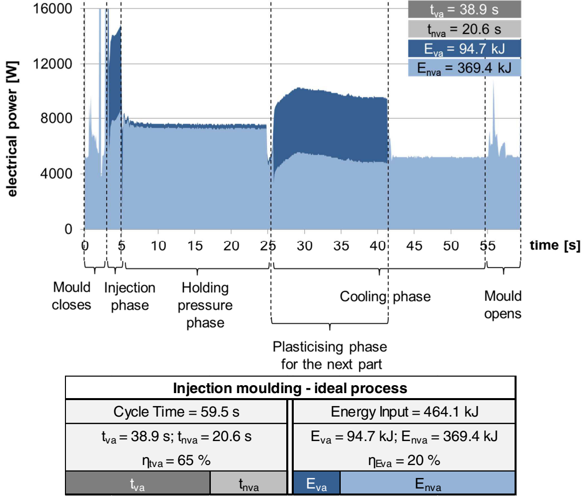
- Forming energy

The forming energy is required to inject the melted mass into the mould against the flow resistance [9]. Based on the process parameters set, it is calculated as follows (equation 4):

$$\begin{aligned}\text{Forming energy} &= \text{Injection force} * \text{Injection hub} \\ &= \text{Injection force} * \text{Piston surface} * \text{Injection hub} \\ &= 1200\,bar * 1.260 * 10^{-3}\,m^2 * 0.100\,m \\ &= 4{,}2\,Wh = 15{,}1\,kJ\end{aligned} \tag{4}$$

As described, in polymer processing the plasticising phase (melting energy) as well as the injection and the holding pressure phase (forming energy) are considered value-adding. The changeover point from the injection phase to the holding phase is at 95% fill of the mould. This means only 5% of the injection volume are left in the barrel at the changeover from the injection to the holding phase [11]. In other words 95% of the theoretical forming energy are assigned to the injection phase and 5% to the holding phase.

Now, as shown in Fig. 8, the following dual energy signature results from the actual energy requirement and the calculated melting and forming energy.



Injection moulding - ideal process	
Cycle Time = 59.5 s	Energy Input = 464.1 kJ
t_{va} = 38.9 s; t_{nva} = 20.6 s	E_{va} = 94.7 kJ; E_{nva} = 369.4 kJ
η_{tva} = 65 %	η_{Eva} = 20 %
t_{va} t_{nva}	E_{va} E_{nva}

Fig. 8. Dual energy signature of an **ideal** injection moulding cycle

Both methods for dualising can be used for evaluating the production process in respect of its efficiency. Both lead to similar results and require only little time for application.

In the industry the ‘idealised process’ has proved to be well suited. The energy signatures are recorded during processing. Calculation of the value-adding elements takes place subsequently, i.e. there are no production losses.

The dual signatures show a high value-adding efficiency in terms of time, which is achieved due to the fact that the cooling phase and the plasticising phase (for the next component) process sequences run in parallel.

The low value adding efficiency in terms of energy shows, however, up to now the energy efficiency of the processes obviously has not been in the focus of interest. Possibilities for improving the process in terms of energy as well as in terms of time are identified below.

4. Optimisations in plastic injection moulding

Electric energy (W) is the integral of power (P) over time (t). To increase the process efficiency, basically two approaches are possible – see Fig. 9.

- Reducing the process time
- Decreasing the power level

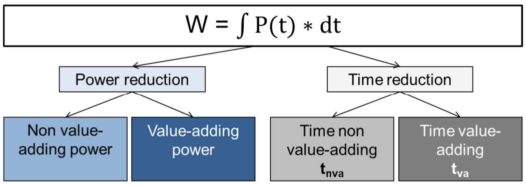


Fig. 9. Approaches to improve the energy efficiency (according to [12])

4.1. Optimisation in terms of time - Reducing the process time

In addition to an increase in productivity, a reduction of the process time leads to energy savings, too. In practice, the setting of the process parameters, holding pressure time and cooling time, are adjusted on the basis of experience. In most cases there is no continuous improvement of these times. The lower the minimum wall thickness of the part, the shorter the holding pressure and cooling times. The container from PBT has a wall thickness of 4 mm – see Fig. 4. For this thickness, recommended values from the relevant literature indicate significant lower values for the holding pressure and cooling phases [11] than those set on the machine under investigation.

- Optimisation of the holding pressure time

The holding pressure phase serves to compensate the shrinkage of the cooling component by the feeding of melted mass. The sealing point limits the holding pressure time. At this point the polymer has cooled down to such an extent that the runner has solidified completely. No more melted mass can enter the mould or leak from it.

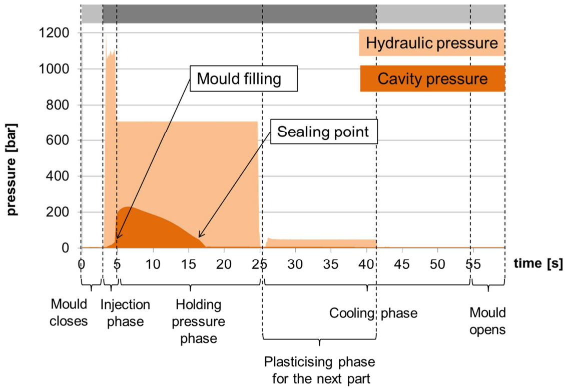


Fig. 10. Cavity pressure and hydraulic pressure curves

Fig. 10 shows the mould cavity pressure curve. The mould cavity pressure increases due to the injection of material. It reaches its maximum due to the compression of the melted mass - see Fig. 10, graph in dark orange. In the course of the holding pressure phase the pressure drops to the sealing point due to the cooling of the moulded component.

To determine the optimal holding pressure time the setting value is raised continually until the increase in weight can be ascertained on the moulded components (without runners) stops [13], see Fig. 11. The sealing point serves as a reference point – Fig. 10. The optimum holding pressure time is 12 s for a moulded component weight of 176.4 g.

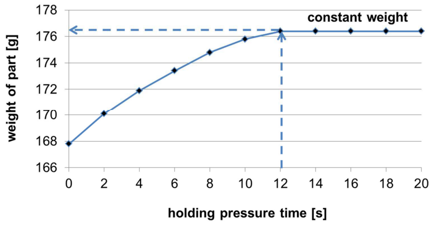


Fig. 11. Determining the holding pressure time by weight check

All in all the cycle time can thus be reduced by 7.7 s, which means a saving of time of approx. 15%. This, in turn, entails a saving of energy of approx. 15 %, too.

- Optimisation of the cooling time

The PBT plastic solidifies by controlled cooling. The heat is removed from the mass inside the mould. Tests have shown that the stability of the moulded component is sufficient for demoulding even without using the residual cooling time. However, deformation occurs here – see Fig. 12 (container).

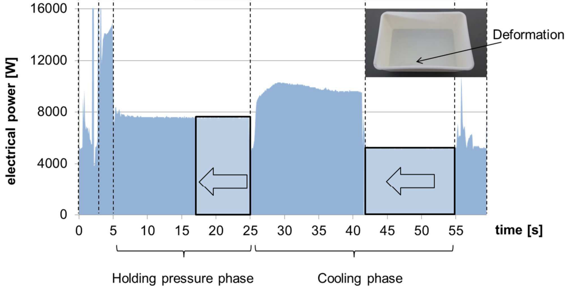


Fig. 12. Reducing the holding pressure and cooling phases

In practice, the cooling time is extended to prevent contraction. This entails a higher energy requirement due to the high base load. The optimisation of the mould temperature or placing the moulded component on its negative mould immediately after demoulding are further possibilities for preventing contraction. It would in consequence be possible to save time of approx. 20%. This reduction in time entails a saving of energy of approx. 15%.

A reduction of cooling time and energy input can also be accomplishment by improvement of the cooling systems via:

- Isolation of the mould
- Optimisation of temperature and flow settings
- Optimisation of mould design (conformal channels)

4.2. Optimisation of energy – Decreasing the power level

- Insulation of the barrel heater

The barrel is heated from outside by heating bands. These heating bands have a relatively poor efficiency because the heat is dissipated to one side only, i.e. towards the barrel [7]. This causes losses of up to 60% by radiation, conduction and convection [7]. The heat losses can be reduced significantly by insulating the barrel, thus saving a heating energy of at least 25% [14]. The total energy requirement of the IMM can thus be reduced by approx. 5%, see Fig. 13. Further energy savings can be achieved by optimising the drive system of the IMM.

- Converting the type of drive and adjusting the clamping unit

From the point of view of energy, electrically operated IMMs or IMMs with a servo-hydraulic system (hydraulic system with a speed-controlled motor) are advantageous. With these drive technologies the power is controlled according to requirement. The hydraulically operated IMM has a force-fitting clamping unit with hydraulic cylinder. This is why the high hydraulic pressure must be kept constant during the locking phase. An IMM can only be converted to servohydraulics if the clamping unit is form-fitting. It would therefore make sense to convert the clamping unit and use a toggle lever, or to install a mechanical locking device. The energy requirement of the hydraulic pump drops by approx. 50% as a consequence of this measure, see Fig. 13.

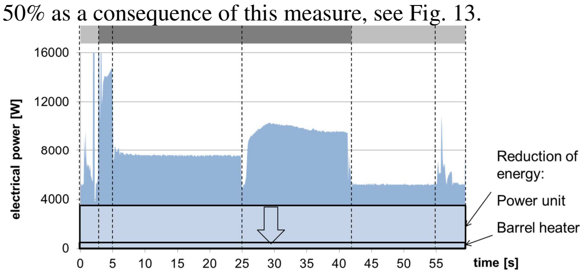


Fig. 13. Lowering the base level

- Connecting a frequency converter ahead

The clamping unit makes sure that the mould is kept together during the injection phase and counteracts the force that tends to open the tool. This tool opening force (F_A) is proportional with the surface (A_p) of the tool cavities projected into the mould parting surface and the maximum tool inner pressure (p_{Wm}) [7].

$$F_A = p_{Wm} * A_p \quad (5)$$

The locking force must be higher than the opening force to ensure that the tool remains closed. Up to now IMMs are kept closed at a constant force, as it is shown in the formula with the constant p_{Wm}.

Actually, the maximum locking force is only required during the injection and the holding pressure phases. With the help of the tool inner pressure curve, see Fig. 10, the locking force required for the individual phases can be determined. The time-dependent tool opening force ($F_A(t)$) can be determined using the formula below.

$$F_A(t) = p_W(t) * A_p \quad (6)$$

This value, multiplied by a safety factor (s), results in the time-dependent locking force ($F_Z(t)$), equation 7.

$$F_Z(t) = F_A(t) * s \quad (7)$$

In practice, the amount of locking force is in most cases equal to the maximum IMM clamping force. Tests have shown that a locking force of 40 t is sufficient for the PBT container (actual IMM maximum clamping force 80 t).

For implementation of this approach, a speed control is arranged ahead of the drive motor of the hydraulic pump. This controls the power according to requirement. The advantage of this optimising measure is that no conversion of the clamping unit is required.

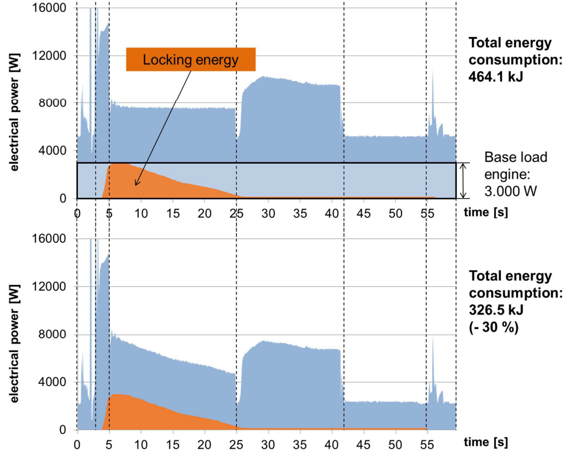


Fig. 14. Saving by adjusting the locking force

Without a speed-controlled drive motor the base load is constantly 3,000 W, see Fig. 14 top, light blue. If a speed-controlled drive motor is used instead, the energy requirement can be reduced to the locking energy needed, see Fig. 14 top, orange. The base load can thus be reduced significantly, see Fig. 14 bottom.

5. Energy value stream mapping

The analysis of the manufacturing processes by dual energy signatures, described in chapter 3, allows it to extend the VSM to an EVSM while maintaining the VSM's inner logic. Fig. 15 shows the process data of the analysed moulded component as an element of an EVSM.

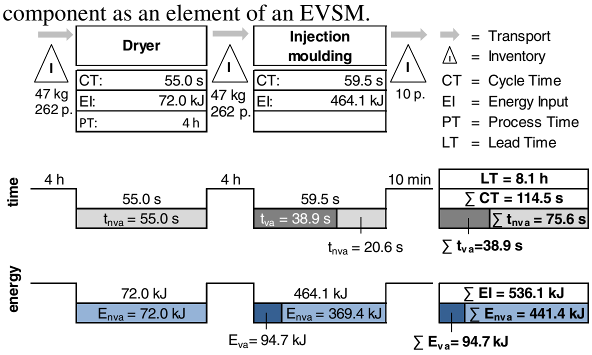


Fig. 15. Injection moulding process in an EVSA

This analysis systematically shows value-adding and non value-adding time and energy in the production process and along the value-stream. At the end of the analysis their sums are in addition contrasted with the lead time, the sum of the cycle times and the total energy input.

6. Summary

The subject of energy efficiency gets more and more into the focus of attention as the prices to be paid for energy rise. Increasing the energy efficiency requires transparency with regard to the energy and time requirements of machinery and plants. By means of the dual energy signatures the energy and time inputs can be differentiated into value-adding and non value-adding elements. In injection moulding processes this can be done by means of 'air filling' or 'idealised process'. While in 'air filling' the process sequences take place without material, the 'ideal process' contrasts the time and energy inputs of an actual process with those of an idealised process. Here the value-adding element of energy is calculated theoretically. Optimising in terms of time and energy can be derived from the analyses and show potentials up to 50 %.

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