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SUSTAINABLE INCREASES OF ENERGY EFFICIENCY BY HOLISTICALLY CONSIDERED STRUCTURES OF FACTORY SYSTEMS

A number of efficient solutions are already in existence today for reducing specific energy and raw material needs, and they are continuously being improved. Since the competition between individual solutions for sustained energy efficiency may prove to be an obstacle to the system as a whole, the interaction of individual elements and sub-systems in complex domains must be considered in an integrated way with an eye to their reciprocal energy effects. What will be the impact of energy savings resulting from innovative approaches and intelligent solutions at a single systemic level on the system as a whole? Do they serve to reduce overall energy costs? What kinds of energy-related information are necessary to answer these questions? This article examines the issue of how dedicated energy savings in the production sector impact on the total energy requirement in factory systems. In one example, process and building are examined together in order to thereby recognize energy relationships. It was demonstrate that waste heat from machine tools has a significant impact on the factory hall climate and therefore on the heating needs of factory buildings. A model calculation demonstrated that energy savings at individual system levels are transferable to the entire system in direct proportion to the energy efficiency of the building.

1. INTRODUCTION

To enable stable production processes, production facilities must be screened from external environmental influences. As the wrappers that surround the production process, industrial buildings serve to protect against humidity, cold, heat, wind, sunlight, noise and pollution, and to prevent tampering and theft. To make waste-free value chains possible, there must be optimal working conditions created for productive processes. Looked at together, the production process and the building structure form a holistic thermodynamic

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system. Accounting for complex factory structures can be accomplished by using the black-box procedure, taking the input-output relations into consideration. This means the building forms the system limit within which the structured processes take place. From this perspective, the manufacturing process should be specifically understood as an internal heat source. The aim of this study was to describe these reciprocal effects in greater detail. The focus was to increase the energy efficiency of machine tools, taking into account their overall effects on the factory system.

2. PRELIMINARY CONISDERATIONS

The premise for studying the importance of wasted heat from machinery on the factory climate was the basic impression that its impact was significant. Case reports, specialized articles [1],[2] and observations confirmed this. In addition, the problem of overheating in the production halls during the summer months also suggested that there would be a causal relationship [3].

Taking account of the climate change agreement and targets [4],[5] to reduce CO_2 emissions, as well as the need to increase resource efficiency in the production sector [6],[7], it come to a question regarding the potential effects of measures responding to these demands. Two possible responses could be the drastic reduction of heat consumption by means of energy-optimized building structures and the substantial reduction of heat requirements in production facilities. But since increased efficiency also means reduced heat output, the contribution from internal heat sources is reduced at the same time. It is thus questionable whether local savings from more energy-efficient machine tools will have the same positive impact upon the system as a whole. In warm months, the effect of reduced waste heat production is positive (it reduces the overheating problem). By contrast, reduced heat from the machine tools during cold seasons lead to a heating deficit. The lost heat must therefore be replaced in order to maintain the required level of room temperature. Unless the structure of the building is changed, it will need additional heating. Considered in terms of the system as a whole, a part of the savings gained is used up in this way. This shows that there are energy interactions. In order to incorporate consideration for this effect in the early stages of design, it makes sense to systematically incorporate it in the overall factory planning process.

3. ENERGY EFFICIENCY ORIENTED FACTORY PLANNING

Planning a factory involves fundamental issues that are relevant to the activities for improving energy efficiency in production. The planning process (Fig. 1) give equal consideration to both the planning and operational phases in order to achieve energy-efficient specifications regarding the type, number and configuration of processes and equipment.

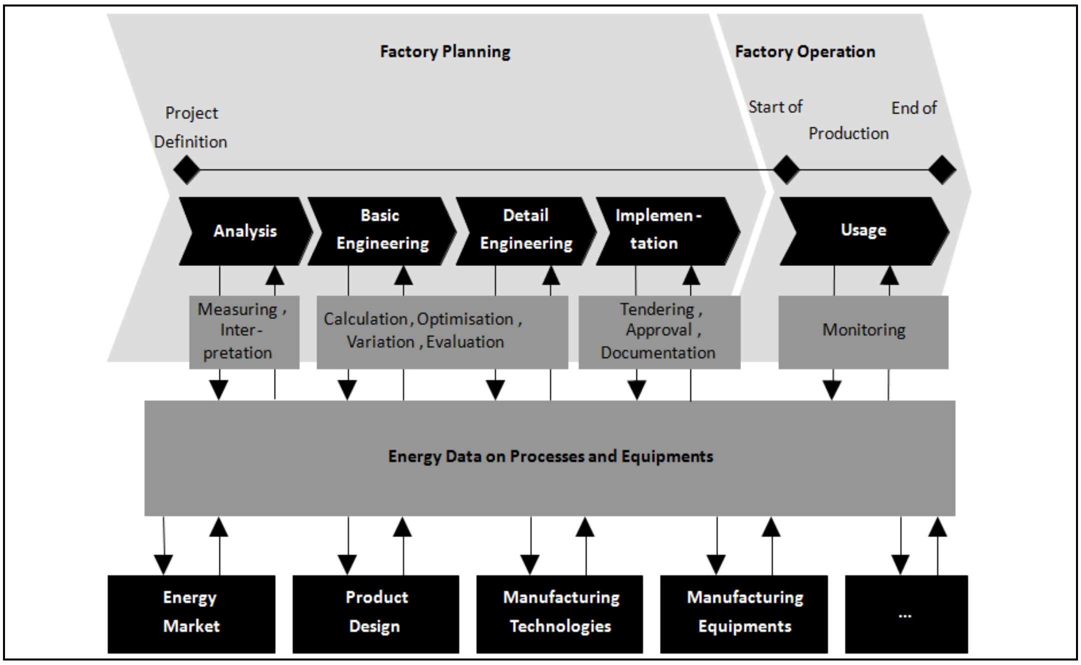

Fig. 1. Systematic factory planning in consideration of energy efficiency [8]

Due to the growing interest in energy-efficient planning solutions, there is an increased need for energy data concerning processes and facilities. These have to be provided to various planners so they may design effective measures. Generally applicable approaches can be formulated for work systems as a whole to permit the achievement of deliberate increases in energy efficiency. These are shown schematically in Fig. 2. It is clear that this involves measures related to products, processes and resources.

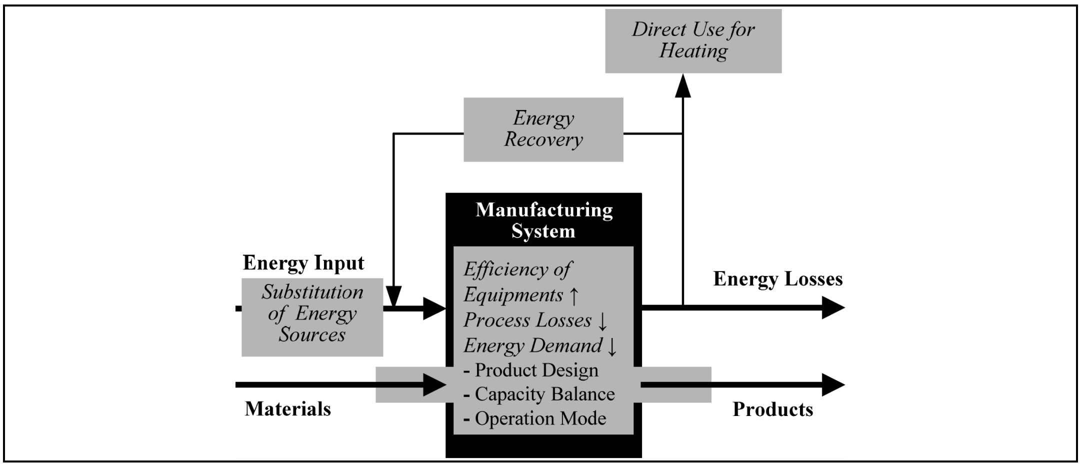

Fig. 2. Basic approaches for improving energy efficiency [9]

The planner must decide at what level of abstraction he can use this systemic approach to project solutions that are based upon policy alternatives.

4. ACCOUNTING APPROACH FOR HEATING ENERGY NEEDS

When accounting for the heating energy demand (E_{heat}) from buildings, thermal losses (Q_{out}) as result of transmission heat transfer (Q_{trans}) across surrounding surfaces and the continuous exchange of air masses (Q_{air}) must be compared to gains (Q_{in}). Positive elements in the balance sheet include solar gains (Q_{sol}), waste heat (Q_{int}) generated by internal processes, machines, units and persons, and heat generated by the heating system (Q_{heat}). The energy fed to the subsystem (E_{sub}) is changed into wase heat (Q_{int}) depending on the specific value of heat transfer (η_{sub})

Waste heat: $Q_{int} = E_{sub} * \eta_{sub}$ (1)
Gains: $Q_{in} = Q_{heat} + Q_{int} + Q_{sol}$ (2)
Losses: $Q_{out} = Q_{trans} + Q_{air}$ (3)
Balance: $Q_{in} = Q_{out}$ (4)
Heating need: $Q_{heat} = Q_{trans} + Q_{air} – (Q_{int} + Q_{sol})$ (5)
Heating energy need: $E_{heat} = Q_{heat} * \eta_{heat}$ (6)

Equations (1) to (6) show that the amount of energy required E_{heat} to maintain the temperature level needed in the hall decreases whenever heat losses Q_{out} are reduced, or when there is an increase in the gains Q_{int} and Q_{sol} or when the efficiency level of the heating system η_{heat} improves. If these gains exceed the heat losses, supplemental heating (Q_{heat}) can be eliminated altogether. This is true in the case of energy-intensive production, unusually high building efficiency (e.g. high-quality thermal insulation, energy cycles) or when ambient temperatures fall above the required hall temperature. For a fundamental understanding of the energy relationships, it must be differentiate between thermal heat and heat energy. Because “Thermal heat” has to be understand as the ideal (net) requirement value, energy considerations must be extended to include unavoidable transfer losses in generating heat beyond the real (gross) consumption value of “heat energy” (see equation (6)).

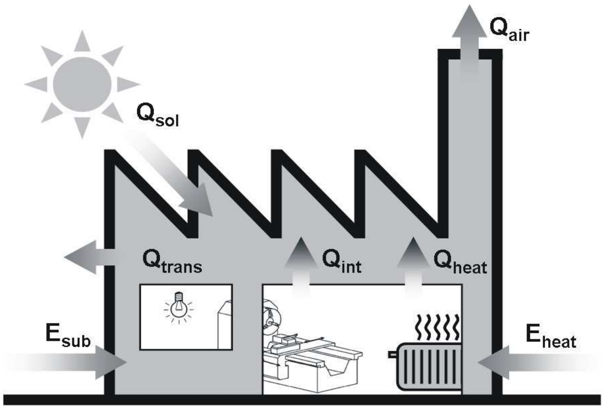

Fig. 3. Schematic view of thermal system connections

According to equations (5) and (6), the energy supplied to the buildings through the heating system (E_{heat}) is determined by the condition of the building cover (Q_{trans} and Q_{air}), the quality of heat production (η_{heat}), the energy intensity in the building operated processes (Q_{int}) and the design, geographic location and orientation of the hall (Q_{sol}) (Fig. 3).

There are a number of different guidelines and regulations that form the basis for calculation algorithms and parameters for the design of buildings (e.g. DIN 4701 or rather the new European standards DIN EN 12831, DIN V 18599, and EnEV2009).

4.1. MACHINES AND PROCESSES AS INTERNAL HEAT SOURCES

Industrial processes are always associated with the generation of waste heat. This is due to fundamental physical principles, such as dry and fluid friction in mechanical systems, which produce entropy due to irreversible dissipation processes. But in addition, Ohmic resistance heating, hysteresis losses and eddy current losses from electrical components also result in heat losses. Moreover, exothermic chemical reactions should also be added to this list.

Basically, all forms of energy can be fully converted into heat. However, these processes are never fully reversible (Second law of thermodynamics). As a consequence of this limited transformability, heat or thermal energy has to be classified as an inferior form of energy.

Most of the waste heat energy is associated with peripheral processes within the machine tools. For example, there are significant energy losses resulting from hydraulics and pneumatic assemblies, control electronics, circulation pumps and conveyor systems [10], [11]. These losses not infrequently exceed the power consumption needs of the core process. The energy required is almost completely converted into heat [12]. The actual proportion will vary depending upon the process, the production design and the design of the machinery. Table 1. provides an overview of process-related heat transfer.

Table. 1. Typical values for heat transfer in typical industrial processes

Process	Heat transfer [%]
Cold forming	approx. 85 – 90
Hot forming	approx. 90 – 95
Machining	approx. 95 – 99.9
Heat treatment	approx. 100
Logistical processes	approx. 98 – 100
chemical processes	Up to 100

In cyclically occurring processes, it can be assumed that the continuous return to the baseline (typically the starting position) also leads to comparable baseline energy levels. Potential and kinetic energy are initially conserved during the process, but always lost by the end. Only a small proportion of this energy is not converted into heat to remain as potential energy in the work piece or its remnants due to plastic deformation (e.g. chips).

4.2. AVERAGE TEMPERATURE PATTERN AS INFLUENCING VARIABLES

Mean monthly temperatures (Fig. 4) form a reasonable basis for the calculation of transmission and air exchange losses. It should be noted that individual maximum and minimum temperatures are not recorded. The anticipated resultant error tends to cancel out over longer periods of time, however, and can therefore be ignored.

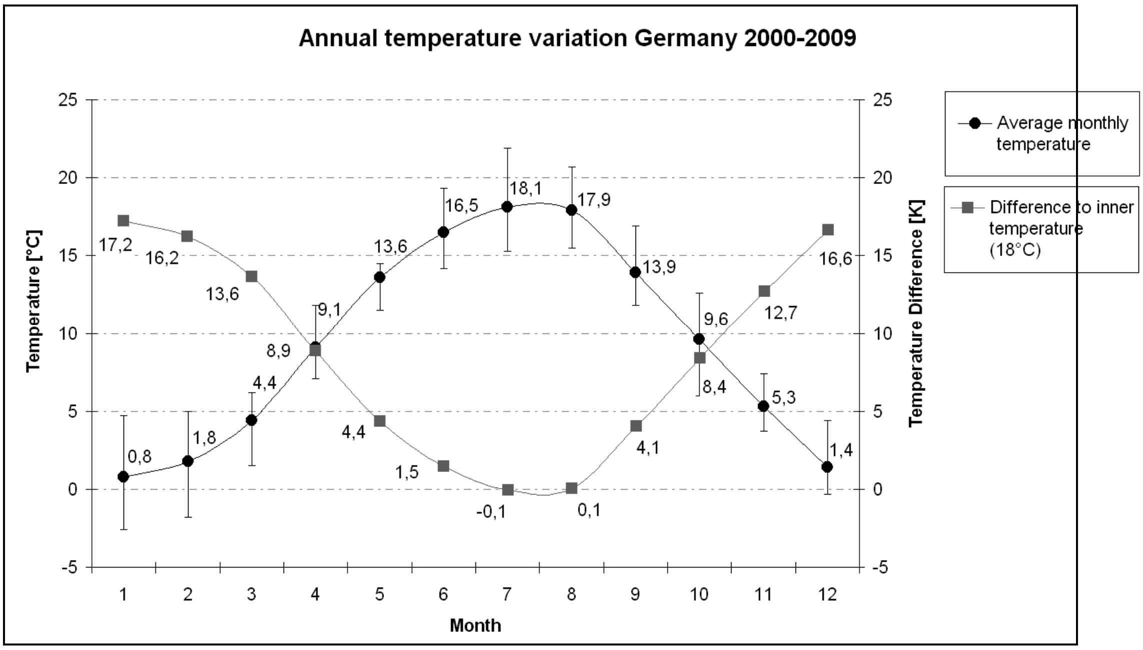

Fig. 4. Annual temperature variation

In the months of July and August, the average outdoor temperature matches the required minimum temperature level of 18° C (medium load; combination of standing and sitting activities [13]) in the hall. The heating requirement for the factory system is therefore close to zero. However, any existing internal heat sources that have an impact on the system should not be ignored. They lead to an increase in internal temperature, resulting in excess heat and longer periods of time without the need for additional heating.

Once the requirement for heat (e.g. thermal heat and hot water) is covered, excesses of thermal energy will occur if more heat is supplied. However, because of the low temperature level of waste heat, it is rarely useful in a practical sense. One alternative to direct use might be a very lossy conversion into electrical or mechanical energy. Fig. 4 also shows the temporal divergence between heat surpluses and deficits over a time period of around six months. To be able to put this potential to use would require long-term storage of large amounts of thermal energy. While technically feasible solutions already exist (e.g. gravel storage [14]), their marketability has not yet been accomplished due to high investment costs.

5. A SPECIFIC EXAMPLE FOR CALCULATING HEATING NEEDS

In Germany, the steel and metal processing industry is dominated by small and medium-sized enterprises [15]. In order to provide a basic illustration of the relationships between planning and systems, a well documented case example from this industry was chosen, which describes the planning and implementation of a "worm gear production" facility [16].

This example demonstrates that the planning steps, beginning from determining function (Which technology?), dimensions (How many machines?), structuring (Machine layout?) and continuing all the way to an economic comparison of different solutions in are considered the core tasks of factory planners. The specific consideration of energy relationships has not found its explicit place in the planning process. Most often, planning focuses on core processes. An unbalanced focus on product creation with inadequate attention to reciprocal effects related to peripheral energy system components (e.g. heating, ventilation), can lead to planning solutions that are inefficient with respect to both cost and energy.

To expand upon the case example, Table. 2 shows the key premises and frameworks that underlie the energy perspective that follows.

Table 2. Basic data for the case example

Example of application - worm gear production			
Industry	Machine construction	**Production shift system**	2 shifts
Segment	Parts manufacturing and assembly	**Operations**	5 days / week
Product	Worm gear production	**Gross production area**	864 m^2
Annual turnover	approx. 6 million Euros	**Net production req.**	34,000 pcs/year
Production personnel	33	**Production Type**	Production Group

In order to accomplish its production program, the company needs the machinery listed in Table 3. The simultaneity factor associated with the process provides a description of the average power consumption of the machines. When combined with the corresponding conversion level (Table 1), this provides the average process-related waste heat performance. These internal heat sources should then be included in subsequent calculations of heating energy. Additional optimization of energy needs can be accomplished in planning the factory by integrating additional parameters (e.g. temporal usage profile, 3D layout). However, the rigid combination of a specific manufacturing process with an associated building system leads to a loss of universality in the potential uses for the facility.

Table 3. Key energy characteristics from the case example

Procedure	**Number of machines [Pieces]**	**Connection power machines [kVA]**	**Simultaneity factor [-]**	**Average heating output [kW]**
Milling	9	16 – 48	0.25	60.8
Turning	4	39	0.25	38.2
Fine machining	2	25	0.25	12.4
Sawing	1	1	0.5	0.5
Broaching	1	26	0.5	12.7
Assembling	1	ca. 10	0.5	4.8
Systems engineering	2	1 - 5	0.5	3
Total	**20**	**528**	**(0.251)**	**132.4**

5.1. CONSIDERATION OF DIFFERENT OPTIONS USING CONSTRUCTION FACTORS

To investigate the impact of building structure on the balance of energy, four different examples were defined for comparison.

Table 4. Parameters used in calculating the comparisons

Input data	**Unit**	**Industrial building before 1980**	**Moderate efficient building**	**EnEV Standard 2009**	**Highly efficient building**
Factory hall width	m	24			
Factory hall length		36			
Average factory hall height		6			
Roof construction	-	Flat saddle roof			
Window area ratio	%	30			
g-value Windows		90	75	60	55
Lightband ratio		10			
Minimum internal temperature	°C	18			
Maximum internal temperature		26			
Set back not below		16			
Average U-value walls	$\frac{W}{m^2K}$	1.25	0.75	0.35	0.25
Average U-value roof		1.5	0.85	0.35	0.2
Average U-value bottom slab		1.25	0.75	0.35	0.25
Average U-value windows		5.2	3.25	1.9	1.3
Average U-value lightband		6	4	3,1	2
Thermal bridge surcharge		0.2	0,1	0,1	0.05

Permitted free air change	$\frac{1}{h}$	1	0.85	0.5	0.2
Min. total air change		3			
Heat recovery ventilation	%	0	30	40	80
Seasonal energy efficiency ratio (SEER) heating system		70	75	80	90
COP air conditioning system	-	2	2.5	3	4
Production staff per shift		16			
Machine waste heat output (ø)	kW	132.4			
Annual operating hours	h	3968			

- Industrial building before 1980 (Unmodernized old construction
- Moderate efficient building (Modernized existing buildings, between 1990 and 2000)
- EnEV Standard 2009 (New construction meeting the minimum standard EnEV2009)
- Highly efficient building (Low energy consumption construction based on EnEV2009)

The input parameters for the construction shells underlying the calculations are presented in Table. 4.

6. RESULTS

Taking into account the conditions specified, the heating and heating energy requirements of the individual case studies could be calculated. This was carried out on the basis of average monthly temperatures over the last 10 years (see Fig. 4). As a result of the technical problems described in section 4.2, regarding the usability of heat surpluses, these were discarded and were not included in the total requirement. The capacity utilization of the machines remained unchanged, meaning that the heat-processing performance remained constant throughout the year. The utilization factor listed in Table. 3 takes into account the average performance of machinery/production equipment over long periods of time.

6.1. TYPE DEPENDENT INFLUENCE OF MACHINE WASTE HEAT

For further comparison of the four variants, three different usage scenarios were considered. This resulted in appropriate combinations of user profile and building stock. The calculation basis (100%) was a state-of-the-art machine hall at full capacity. This corresponds to an average heat capacity of all machines of 132.4 kW (see Table. 3).

1. Scenario: hall without internal heat sources (0% heat emission)
2. Scenario: 30% more efficient machine tools (70% heat emission)
3. Scenario: Machine tools – state of the art (100% heat emission)

Fig. 5 shows that, without internal heat sources, constant heating is required (annual heating requirement > 0).

As expected, with 100% machine heating, the remaining heating requirement is clearly reduced. In buildings using and/or exceeding state of the art technology, additional heating is not required. When using energy-efficient machine tools (scenario 2=70% heat emission), the heat dissipation percentage stated is only achieved in well insulated buildings.

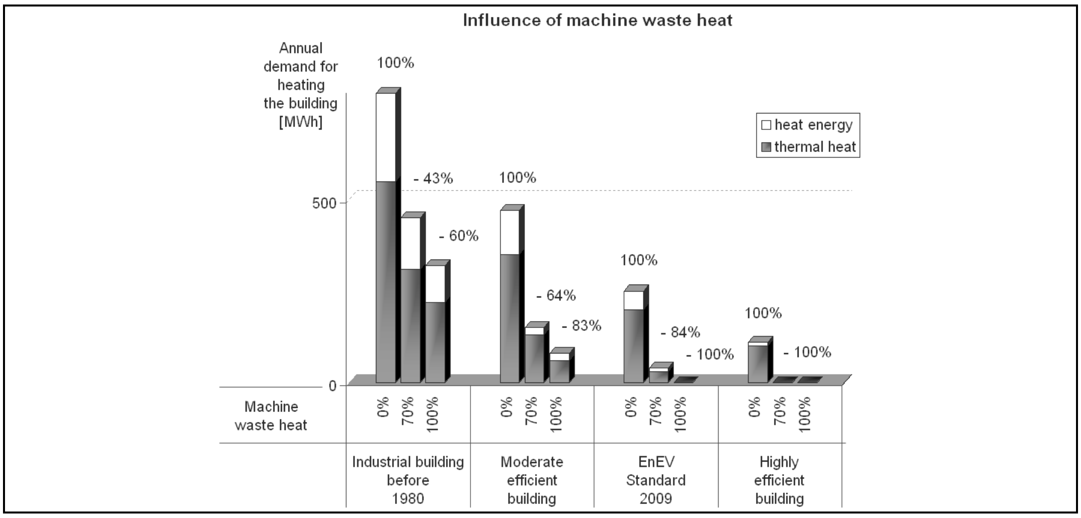

Fig. 5. Influence of machine waste heat

Taking as an example the medium-sized enterprise (worm gear production), the machine waste heat has a significant effect. This confirms the relevance of machine waste heat on the indoor climate. The impact is felt even with a lower output per square meter, for example, during less energy-intensive production (scenario 2).

6.2. IMPACT OF INCREASED ENERGY PRODUCTIVITY

To carry out comprehensive assessment of the impact of efficiency measures on energy consumption, the results must be further differentiated. In so doing, it is helpful to consider primary and final energies. For consumers, final energy is of primary economic relevance, as energy providers charge for it depending on use. From an ecological perspective, however, primary energy, as a naturally occurring resource, is of greater importance as it has not been converted into another energy form, thus incurring loss. The energy needed to produce the final energy can be calculated in the form of primary energy factors (f_p) [17],[18]. The energy carrier (such as electricity or heating oil) is chosen as part of the factory planning decisions, and determines the consumption of primary energy.

Figure 6 illustrates the effect of a 30% reduction in machine waste heat on the total energy requirement of the balanced system.

Generally speaking, a more efficient building has a greater energy saving effect. It is evident that only high performance buildings maintain an energy saving level close to the level possible, (29%) in relation to the primary energy consumption. This can be explained in the fact that electrically generated machine waste heat (f_p=2.6) is substituted by cheaper primary heating energy, such as oil or gas (f_p = 1.1).

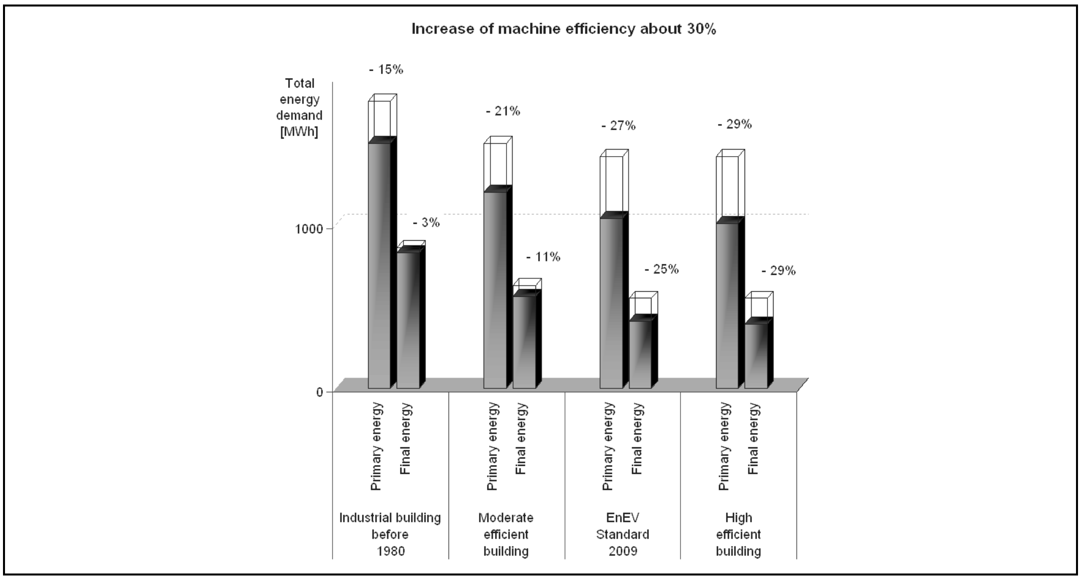

Fig. 6. Increase in machine efficiency by 30%

7. CONCLUSION

In conclusion, it is evident that measures to increase energy efficiency and reduce costs are to be fully observed and implemented. In order to be deemed successful overall, machines, processes and buildings must form an efficient unit. For a resource-efficient system, the interdisciplinary cooperation of all those involved, from machine designers, process planners, managers and factory planners to architects is essential. The knowledge of the various departments should be combined, for example in the form of an energy data model to support factory planning and operation. In order to remain effective, users must respond to changes proactively. This means implementing planning objectives and contributing to continual improvement. Furthermore, the underlying data should be examined at regular intervals and adjusted if required.

It has been demonstrated that new and renovated buildings, which adhere to the EnEV2009 standard, allow only minimal energy losses. To optimize inefficient buildings, transmission and air exchange losses should be minimized, contemporary building technology applied and if possible, energy recovery systems employed. The structural optimization of existing buildings can therefore be achieved through the use of adequate insulation and sealing, modern heating and air conditioning systems and heat recovery processes (recuperation). Without such measures, up to 50% of the energy saved could be lost through the additional heating of the entire system. Due to the high transfer losses incurred with conventionally generated electrical energy, from both an economic and environmental perspective, buildings should always be heated using suitable energy carriers (eg gas, oil, wood pellets).

As a general rule, a suitable energy source should be selected for each particular application. This avoids additional transfer losses and conserves finite resources. Sustainable energy efficiency can, however, only be achieved by substituting fossil fuels.

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