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Procedia CIRP 15 (2014) 80 – 85

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21st CIRP Conference on Life Cycle Engineering

Extending Energy Value Stream Models by the TBS Dimension – Applied on a Multi Product Process Chain in the Railway Industry

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Abstract

Energy value stream analysis is used to quickly evaluate the energetic performance of process chains within continuous improvement processes in production companies. Existing approaches focus mainly on capturing and allocation of direct energy demands induced by production machines. However, most approaches lack the holistic perspective, leading to neglect huge parts of the indirect energy demands, caused by the technical building services which are vital to maintain the production conditions. This paper presents an extended approach, targeting to fully distribute indirect energy demands upon specific entities of the value stream by presenting systematic allocation rules, which cause-dependently break down peripheral energy demands.

Selection and peer-review under responsibility of the International Scientific Committee of the 21st CIRP Conference on Life Cycle Engineering in the person of the Conference Chair Prof. Terje K. Lien

Keywords: Indirect energy; allocation rules; TBS; energy value stream; energy transparency; energy management; continuous improvement; rail industry

1. Introduction

The International Energy Agency has stated that the building sector is the largest entity demanding energy in the United States. It accounts for around 41% of the total United States (U.S.) energy use [1]. As the energy demanding processes in such entities are mostly technical building services (TBS), the importance of TBS becomes clear and can also be translated for factory buildings. Still, TBS-related energy costs are commonly just considered as necessary overhead costs and are rarely questioned or considered in continuous improvement processes. Therefore, an allocation of the TBS-related indirect energy demands to the energy value streams of products is vital in order to indentify the real energetic hot-spots within a factory and derive improvement measures [2]. Thus, rules for a correct allocation (e.g. value adding timed depended or allocated area depended) of peripheral equipment induced energy demands need to be integrated in value stream assessment methodologies ensuring an adequate effort.

Against this background this paper presents a methodology based on allocation rules that enable manufacturing enterprises to assess extended energy value streams, considering all peripheral equipment with low effort in time while sustaining an acceptable level of accuracy. The new methodology will be demonstrated within a rail industry case of a manufacturing plant of the Siemens AG in Europe.

Selection and peer-review under responsibility of the International Scientific Committee of the 21st CIRP Conference on Life Cycle Engineering in the person of the Conference Chair Prof. Terje K. Lien
doi:10.1016/j.procir.2014.06.067

2. State of the Art on Indirect Energy Allocation Methods in Value-Creation Process Chains

2.1. Direct and indirect energy demands

Typically, initial energy workshops in industrial environments put the focus on the main processes and production machines as well as the obvious entities of TBS like lighting. This short-sighted approach, trying to perform an energy flow analysis according to material flow approaches, will lead to wrong priorities and unsatisfactory return of invests [3]. In practise, the main processes and machines rely on a far larger subsystem of peripheral elements. To classify these obvious and hidden energy demands, Seow and Rahimifard have given distinction to the terms direct energy, caused by value adding processes and indirect energy, caused by activities to maintain the production conditions, in which the value adding processes and auxiliary processes are carried out [4].

In order to differentiate between various TBS, Schenk *et al.* have classified the peripheral elements along a peripheral order. The peripheral order defines the functional adjacency of a TBS element to a defined machine, respectively a value adding process [5]. Fig. 1 refers to this functional adjacency and lists peripheral elements of the TBS from first to fourth order. Such elements are considered as peripheral processes with an indirect energy demand. In contrast to the definition of Seow and Rahimifard the linked peripheral processes are also considered as indirect energy demanding entities.

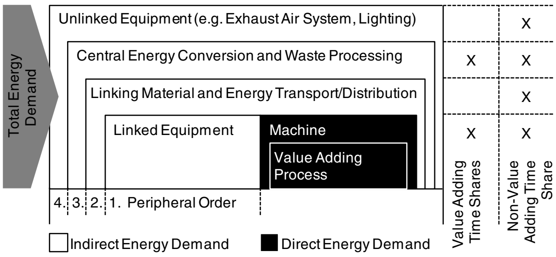

Fig. 1. Peripheral order of TBS elements indicating the functional adjacency (referring to the peripheral order of [5])

First order elements are defined to have the highest adjacency to the actual value adding processes and are considered as linked equipment (e.g. decentralized coolant treatment or air filtering systems). Second order elements are directly linking single machines and equipment in order to realize material and energy transport and distribution. Third order elements are providing centralized TBS such as energy conversion (e.g. compressed air generator) or waste processing equipment (e.g. centralized coolant filter). Fourth order elements have the lowest possible adjacency and are considered to be unlinked services on building level (e.g. exhaust air systems, lighting or social rooms). Fig. 1 will be subsequently used to indicate which of the existing methodological approaches in literature are addressing any of the specific peripheral orders and are giving related allocation rules.

2.2. Existing dynamic approaches

In the domain of dynamic approaches Herrmann and Thiede as well as Hesselbach *et al.* introduced the holistic perspective on production systems stressing the importance to consider all elements: machines as well as the TBS [6][7]. Later, this perspective was transferred by Thiede into a holistic energy flow oriented simulation, capable of calculating and evaluating the dynamic energetic interactions between the actual value adding processes and generic TBS models up to the third peripheral order [8]. This predictive approach along with others from the simulation domain allows a very specific allocation of TBS elements to single value adding processes without being applicable for static, retrospective approaches.

2.3. Existing static retrospective assessment approaches

In case where the specific energetic transformation functions for value adding processes and especially peripheral processes are not given, dynamic predictive allocation methods are difficult to apply. Therefore, static retrospective approaches are needed for initial energy assessments within process chains. Static approaches target to break down physical measurements (e.g. field data from existing energy metering systems or external load profiles form energy billing services) into non-value adding and value adding time shares of production processes based on allocation rules. The identified non-value adding processes are allocated retrospectively according to production planning (e.g. job order management or resource scheduling) to specific processes in order to indicate the 'true' energy needed to accompany the value creation process.

As the Environmental Protection Agency (EPA) of the U.S. has introduced energy value stream mapping (EVSM) to the American society, Erlach and Westkämper have introduced the term energy value stream analysis (EVSA) in the German research community. However, both approaches are specifically focussing solely on the value adding processes and neglect most of the peripheral entities [9][10].

A more recent approach by Schilling *et al.* extends the energy value stream into the supply chain level, thus including also inter-factory indirect energy demands due to transportation [11]. Although, they address the same basis of peripheral orders as Schenk *et al.* (see Fig. 1), they only take inter- and intra-factory transports (second peripheral order) as indirect energy demands into account.

Whereas, Reinhard *et al.* include the first three orders into their approach by considering the distribution network of compressed air and the centralized compressed air generation in order to be able to indicate losses and ineffective pressure levels for very specific peripheral entities [12]. More specific and also including the fourth peripheral order is the approach presented by Bogdanski *et al.*, defining related TBS (linked equipment) and overhead TBS with relevance to the whole process chain (unlinked equipment)[13]. The allocation of indirect energy demands with overhead functions results in an equal distribution over the number of value adding processes.

For allocation of fourth order indirect energy demands Seow and Rahimifard propose a calculation based on ‘zones’ of equal condition (e.g. temperature, humidity, air purity) [4]. The allocation is performed by dividing the total energy for the entity of fourth peripheral order by the amounts of products processed in the corresponding zone per period of time.

As shown in the overview, the majority of the presented approaches can only partially give a solution to the allocation problem of indirect energies. In the following section the research gap and the methodological requirements will be derived.

2.4. Research gap analysis

The investigation on existing approaches within the state of the art has shown that the majority of the practise oriented energy analysis methods are referring to the value stream visualization. This graphical way to differentiate between value adding and non-value adding shares of time has been very important in the lean production paradigm ever since to identify hot-spots and areas of improvement. The missing methodological background leads to a huge barrier for management induced energy savings. Three major phenomena have been identified:

- the investor/user-dilemma (a.k.a. split incentives), where owners of factory buildings try to minimize investment costs for energy efficient technologies since the resulting higher running and energy costs from using less efficient technology will not be paid by them but by their tenants, renters or other users [14][15],
- the actor/beneficiary dilemma, where the cost savings induced by the investment into more energy efficient technology or equipment is divided upon all cost centers due to equal distribution of overhead costs in controlling caused by not cause-depended cost allocation,
- the lack of energy transparency within energy distribution structures [16].

As an essence, it will be of high importance to provide a methodology for practitioners who have the demands to systematically identify energetic hot-spots within production sites considering the holistic perspective [3].

3. Requirements for an extended perspective integrating indirect energy demands

The gap analysis has shown a mismatch between scientific and especially industrial needs on one side and the current status of existing solutions on the other. Based on this demand the new approach should provide the following features:

- A standardized and comprehensible way to allocate and visualize the demands of all energy transforming entities cause-dependently mapped to specific processes.
- A calculation based on easily accessible information like production plans, shift-plans, factory layouts and field data. This includes parameters like distances, areas, times and nominal power demands, energy meter readings as well as mobile one time measurements.
- No necessity for long-term measurements, detailed machine analyses on component level or long term observations of processes.
- A method pursuing a practical, hands-on approach where data is easily derivable incorporating a view where certain peripherals are part of the value chain.
- A standardized form of data input, compatible with hands-on workshops in industrial environments.

4. Derivation of the methodology for the extended perspective

4.1. Classification of indirect energy demands

Production machines demand diverse forms of energy over specific amounts of time in order to create value, e.g. a material removal process. During non-value adding times there is still a certain amount of energy needed to allow ‘ready for production’ modes. Moreover, the indirect energy demands of adjacent peripheral equipment also have to be taken into account. Fig. 1 classifies which of the indirect energy demands resulting from the utilization of first to fourth order peripheral equipment can be allocated to value adding times or non-value adding times.

Linked equipment can be classified as peripherals that are exclusively allocated to one production machine. Examples are exhaust air filters for coolant mist extraction, coolant treatment and filtering, tempering units for casting processes or de-central energy transformers. The allocation method has to cope with the conflict of uncertainty due to non synchronous utilisation of value creating processes and peripheral equipment. Therefore, a time-efficient and a simplified method will have to be presented, which allows an increased accuracy, if needed, after a fist analysis in the value stream design phase.

Linking equipment for material transport and energy distribution are second order peripheral entities that can be allocated specifically to two or more production machines that are being linked by it. Examples are overhead cranes linking multiple production machines or workstations, transport belts linking two entities or the compressed air network linking central energy conversion and multiple energy ‘sinks’. Transport and distribution is per-se classified as non-value adding and needs to be allocated to all physically linked entities from source to sink. Standby as well as effective power demands will need to be considered equally. Multiple product transport will need to be considered as well.

Central peripheral equipment is a third order type entity and is therefore considered to be of a lower adjacency as linked equipment even though it can be of the same technical function. Such kind of equipment is for example compressed air generation and treatment, central coolant filtering and treatment units, steam generators or solid waste processing centres. All entities have in common that they can be linked via a material or energy transport. Sources which have a direct link to demands of production machines during value adding times are also considered to be value adding. All others are considered as non-value adding.

Unlinked equipment is of the highest order with the lowest possible adjacency within the considered system boundary. Entities that transform energy in order to provide the demanded conditions of comfort, safety, and health for production machines and staff are considered as such (e.g. heating systems for factory buildings, building ventilation and air purification). Such systems are demand and cause driven. Highly emitting processes are cause drivers and human workplace conditions are demand drivers. To ease up this philosophical cause and demand discussion the effected range will be considered in the allocation rule. In case of a factory shed, the full area of the shed is affected by the factory's heating system, no matter whether the considered area is demanding the heating energy or not.

4.2. Allocation of indirect energy demands caused by TBS to value adding manufacturing processes

In this section a set of practise oriented, simplified allocation rules for direct as well as indirect energy demands for all four identified levels of peripheral orders are presented. With the help of exemplary load profiles, Fig. 2 indicates graphically, how a break down to value adding and non-value adding times of processes and linked equipment can be performed. It is of high importance to take into consideration that the presented approach does not aim to most precisely identify and allocate exact value adding shares of energy but rather to provide the most practise oriented approach. Hence, the methodology proposes a step-by-step increase in the level of detail in analysis and related metering and data capturing efforts based on the results of the initial analysis.

Nomenclature:

VA/NVA	Value adding / Non-value adding
E / P	Energy / Power
start	Start of value creation process
stop	End of value creation process
RUP	Ramp-up phase of machinery or equipment
t_{idle}	Waiting/idle period of transport/machining processes
i-1	upstream process
i+1	downstream process
w	work piece index within a batch/lot [1...*k*] (*k*=batch size)
i	index of process [1...*n*]
l	index of machines/workstations [1...*h*]
j	index of TBS equipment (of any order) [1...*m*]
A_{common}	common/shared area not taken by machines

Direct energy allocation to a process/machine:

$$E_{l,i,VA} = \overline{P}_{l,i,VA} \cdot \sum_{w=1}^{k} \Delta t_{w,i,VA} \quad (1)$$

$$\mathrm{E}_{\mathrm{l,i,NVA}} = \overline{\mathrm{P}}_{\mathrm{l,i,NVA}} \cdot \left(\sum_{w=1}^{k} \left(\mathrm{t}_{\mathrm{w+1,i,start}} - \mathrm{t}_{\mathrm{w,i,stop}} \right) + \mathrm{t}_{\mathrm{l,i,RUP}} + \mathrm{t}_{\mathrm{l,i,idle}} \right) \quad (2)$$

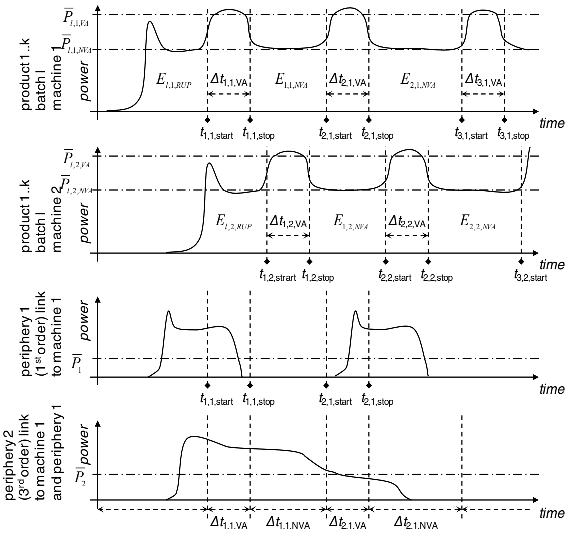

Fig. 2: Schematic application of practice-oriented allocation rules for indirect energy of equipment with 1st and 3rd peripheral order.

Indirect energy allocation for first peripheral order:

$$\mathrm{E}_{\mathrm{i,l,j,VA}} = \overline{\mathrm{P}}_{\mathrm{j}} \cdot \sum_{w=1}^{k} \Delta \mathrm{t}_{\mathrm{w,i,VA}} \quad (3)$$

$$\mathrm{E}_{\mathrm{i,l,j,NVA}} = \overline{\mathrm{P}}_{\mathrm{j}} \cdot \left(\sum_{w=1}^{k} \left(\mathrm{t}_{\mathrm{w+1,i,start}} - \mathrm{t}_{\mathrm{w,i,stop}} \right) + \mathrm{t}_{\mathrm{l,i,RUP}} + \mathrm{t}_{\mathrm{l,i,idle}} \right) \quad (4)$$

Indirect energy allocation for second peripheral order:

$$\mathrm{E}_{\mathrm{i,j,NVA}} = \tfrac{1}{2} \overline{\mathrm{P}}_{\mathrm{j}} \cdot \Delta \overline{\mathrm{t}}_{\mathrm{transport,i-1,i}} + \tfrac{1}{2} \overline{\mathrm{P}}_{\mathrm{j+1}} \cdot \Delta \overline{\mathrm{t}}_{\mathrm{transport,i,i+1}} + \left(\overline{\mathrm{P}}_{\mathrm{j}} \cdot \mathrm{t}_{\mathrm{idle,j}} + \overline{\mathrm{P}}_{\mathrm{j+1}} \cdot \mathrm{t}_{\mathrm{idle,j+1}} \right) \cdot \tfrac{1}{\mathrm{n}_{\mathrm{affected}}} \quad (5)$$

Indirect energy allocation for third peripheral order:

$$\mathrm{E}_{\mathrm{i,j,VA}} = \frac{\overline{\mathrm{P}}_{\mathrm{j}}}{\mathrm{n}_{\mathrm{affected}} + \mathrm{m}_{\mathrm{affected}}} \left(\Delta \mathrm{t}_{\mathrm{i,VA}} \right) \quad (6)$$

$$\mathrm{E}_{\mathrm{i,j,NVA}} = \frac{\overline{\mathrm{P}}_{\mathrm{j}}}{\mathrm{n}_{\mathrm{affected}} + \mathrm{m}_{\mathrm{affected}}} \left(\Delta \mathrm{t}_{\mathrm{i,NVA}} + \frac{\Delta \mathrm{t}_{\mathrm{unasigned}}}{\mathrm{n}_{\mathrm{affected}} + \mathrm{m}_{\mathrm{affected}}} \right) \quad (7)$$

Indirect energy allocation for fourth peripheral order:

$$\mathrm{E}_{\mathrm{i,j,NVA}} = \overline{\mathrm{P}}_{\mathrm{j}} \cdot \frac{\left(\mathrm{A}_{\mathrm{l}} + \frac{\mathrm{A}_{\mathrm{common}}}{\mathrm{h}} \right)}{\mathrm{A}_{\mathrm{total}}} \cdot \left(\Delta \mathrm{t}_{\mathrm{i}} + \Delta \mathrm{t}_{\mathrm{RUP}} + \Delta \overline{\mathrm{t}}_{\mathrm{idle}} \right) \quad (8)$$

Eq. 1 describes the allocation of direct energy to a process *i* based on the average value adding process time (average over a batch or lot *k*), whereas eq. 2 allocates the non-value adding energies based on the average non-value adding times within one batch. Well aware of the fact that value adding energy shares are to be calculated by the

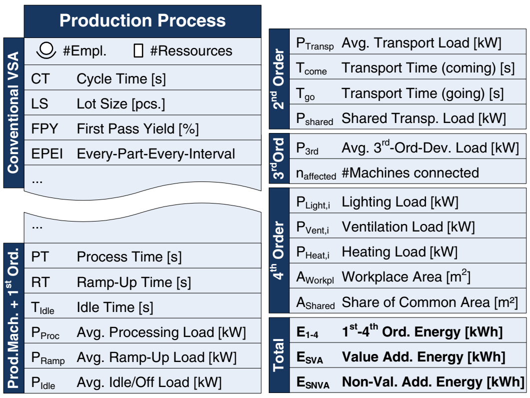

Fig. 3 Classification of peripheral systems in value stream box layout.

mathematical difference between air cut and effective cutting as an example for chip cutting processes, this allocation method is not applicable in practice due to its high experimental measurement efforts. Following this simplification rule based on value adding time spans, eq. 3 and 4 allocate indirect energy demands of directly adjacent TBS equipment. Another practice-oriented simplification applied is the average determination of the equipment's power demand *Pj* in order to draw aside the fact that peripheral equipment's power demand must not necessarily be time synchronous, as Fig. 2 indicates, with its linked production processes. This smoothing of power profiles leads to an acceptable impreciseness to capturing effort ratio. First and third order peripheral equipment energy demands are split into value adding and non-value adding shares because they are considered to be directly energetically coupled (bound by energy distribution) with one (applies for first order) production process or a definite number of machines and peripheral equipment ($n_{affected}$ and $m_{affected}$). Second and fourth order equipment's energy demands are considered to be unbound and therefore explicitly non-value adding.

The allocation rules are given by eq. 5 and 8. Energy demanded by transportation equipment (eq. 5) is evenly split between the downstream and upstream time shares. If transportation equipment (e.g. overhead cranes) is used to link more than two processes which cause unallocated idle times, the idle period is evenly allocated to all affected processes ($n_{affected}$). Fourth order energy demand is allocated in a first step in reference to Seow and Rahimifard in relation to the acquired area of the process, the common areas and the area acquired by the TBS equipment A_{common} gets evenly shared along all machines/workstations *h*.

Fig. 3 shows exemplarily layout of an extended process box for energy value stream visualisation with all inputs which need to be captured. The essential results are indicated in the 'Total' row which can be unfolded in order to analyse the shares of value adding and non-value adding shares of energy caused by one production process in each peripheral order.

5. Case study application in railway industry sector

5.1. Description of the industry case environment

The introduced methodology was applied at an existing rail factory of the Siemens AG. Focus was set on one building where different kinds of production and assembly processes take place (e.g. welding, milling, grinding and inspection) of fully automatic as well as of manual type. Manual processes are often executed in parallel depending on workforce and machinery allocation. Several peripheral systems ranging over all four orders of TBS elements are required to provide a safe and functional working environment (e.g. heating, ventilation, waste processing and lighting). The existing layout of machinery and equipment is highly influenced by local constraints and thus machines cannot be arranged according to the product flow. This leads to complex material transports between the different production processes and shop-floor areas. Due to this fact, the energy demand of the TBS entities is expected to be very high compared to the regular production processes.

5.2. Discussion of Results and Data Analysis

Fig. 4 depicts the final results achieved by applying the introduced methodology. It shows the direct and indirect energy demand of six consecutive manufacturing processes, forming an integral part of the multi-product value stream for metro cars. Three products (A, B, C) are compared that run through the same process steps. Product geometries and quality requirements vary between each product, leading to different sub working steps, process times and an execution on product specific workplaces, hence requiring the modelling of product specific value streams. The results highlight the importance of indirect energy demands compared to the direct ones as they are up to twice as high (e.g. process 1 and 4). In this case indirect energy demands

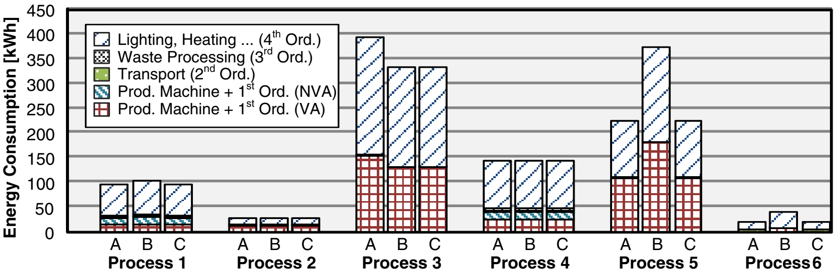

Fig. 4: Direct and indirect energy demands during six process steps comparing three products (A, B, C)

is mainly caused by fourth order peripheral systems – heating, lighting and exhaust systems (ordered with decreasing relevance). Energy demand of transport systems and waste processing are almost negligible which is reasonable as their relative importance decreases with long process times.

The results allow the overall comparison between value- and non-value-adding activities broken down to processes and products. In this case a high improvement potential can be identified within the non-value-adding activities, which make up about 60% of the overall demand. Hence, for increasing energy efficiency the peripheral systems were focused in first instance. A first identified measure for reducing the demand is for example the use of local exhaust systems for welding applications as this will decrease the utilization time of the central, energy intensive exhaust system that is controlled by air quality sensors (see also [17]). Further improvements can be achieved by different strategies to reduce the lighting demands through intelligent control systems or different lighting technologies as already introduced in [18]. Furthermore, the methodology highlights the relevance of process time reductions, since the processes with the highest duration tend to be the ones with the highest energy intensity.

6. Critical Review and Outlook

By applying the presented methodology it is not only possible to generate a detailed insight into the energy flows of the various value adding processes, but it also enables the viewer to differentiate between single products within the same process step, by creating multiple value chains within one methodology. In addition, not only the direct energy demands are made transparent – moreover, the total variety of peripheral systems, directly linked ones as well as the ones with a very loose adjacency, are fully considered and cause-dependently broken down to each process of the value chain, enabling to calculate the true embodied energy of production of products. The presented case study of a manufacturing building in the railway industry clearly showed that it is possible to practically apply the methodology using empiric measurement data of the total energy demand of a whole building in combination with a few detailed energetic measurements on machine and equipment level.

Hence, one can see that the question of which production process is actually responsible for the energy demand of shared peripheral systems is highly complex and can of course not finally be answered by solely area- and time-based formula, implying a more detailed meter based strategy for most precise energy and cost-allocation.

Besides ongoing validation of the proposed methodology in other industry cases, further studies will pursue the enhancement of the pragmatic, applicable solution to suit the continuous improvement processes within the framework of ISO 50001 energy management. Next work of the authors will be to extend the methodology to the environmental evaluation perspective, taking also linked auxiliary materials (e.g. cutting fluids) and environmental impacts of materials and energy forms used into consideration.

7. Acknowledgements

The research leading to the presented results has received funding from the European Community's Seventh Framework Program (FP7/2007-2013) under the grant agreement no. 285363 with the title 'Eco Manufactured Transportation Means from Clean and Competitive Factory' (EMC²Factory). Visit www.emc2-factory.eu for more info.

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