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Integrated technique assessment based on the pinch analysis approach for the design of production networks

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Abstract

Integrated Process Design aims at a holistic approach to process design, retrofitting, and operations planning. Cost and energy "targets" (i.e. the minimum possible values for these objectives) can be calculated based on pinch technology, which defines the enthalpy at which the hot and cold process streams are separated by the minimum temperature difference in heat exchanger networks. This approach is well established in process engineering and has recently been expanded to mass pinch analysis. The combination of engineering, process integration and Operations Research allows the consideration of a variety of economic and environmental process attributes for an integrated technique assessment, as a case study in the sector of automotive serial coating shows.

Keywords: Environment; Energy; VOC (volatile organic compound); Process optimisation; Pinch technology

1. Introduction

Integrated technique assessment requires holistic approaches, considering impacts to all environmental media (air, water, land) and energy consumption, as requested by the IPPC-Directive (96/61/EG) on Integrated Pollution Prevention and Control. "Best Available Techniques" (BAT) are being determined in a cross-media evaluation of all implemented and emerging techniques in relevant industrial sectors including environmental, social and economic aspects (EC, 1996; Geldermann and Rentz, 2001). Likewise, environmental management consequently depends on managing these numerous criteria simultaneously (Geldermann and Rentz, 2005).

While BAT are techno-economically characterised for each industrial sector individually, the

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actual planning and optimisation of emission reduction techniques aim at further process integration. Currently, Industrial Ecology is emerging as a new field of research focussing on an improvement of products and industrial production processes under ecological aspects (Graedel and Allenby, 2003), while promoting Clean Technologies (Clift and Longley, 1995; Leffland and Kaersgaard, 1997). It should be noted, however, that process optimisation and materials reuse have a long tradition in process engineering (Dunn and Bush, 2001) and is widely applied in process intensification for existing designs (Douglas, 1988).

Methodological parallels between process optimisation and Operations Research have been pointed out by several authors. For example, integrated production planning for ammonia synthesis takes into account by-products, residues and emission taxes (Penkuhn et al., 1997). Unit operations, modelled by the process simulation software ASPEN PLUS, are also the basis for a mixed integer linear programming (MILP) of the recycling process of demolition wastes and products at the end of their lifetime in the steel industry (Spengler et al., 1997). Other examples are the combined use of Goal Programming (GP) and the Analytical Hierarchy Process (AHP) for prioritisation of the different goals of process optimisation, which are demonstrated by a case study on the optimisation of three petrochemical plants (ammonia-, refinery- and polypropylene-plant) influenced by social, economic and environmental objectives (Zhou et al., 2000). In contrast to these ''as a whole'' optimisation approaches and centralised-view analyses, agent-based approaches focus on decentralised installations within a supply chain (García-Flores and Wang, 2002). Using simulation and a formalised language between the agents, a batch process for the manufacture and supply of paints and coatings can be modelled and design implications can be identified, which highlight agile structures for a competitive advantage (García-Flores et al., 2000).

These approaches break the optimisation objective down into its different dimensions and define targets, which can be used to implement certain technological standards. In particular, the optimisation of energy use has a long tradition within chemical and process engineering. Especially exergo-economic approaches can be used to analyse the energy flows within the production process and thereby further the transparency of cost development within the processes of the plant modules (Tsatsaronis et al., 1990; Linnhoff and Turner, 1981). Derived from exergy analysis principles, pinch analysis is a systematic approach to techno-economic optimisation of the energy requirements of production networks according to their unit operations. This approach has for example been applied to the assessment of truck coating in a plant in North-America (Roelant et al., 2004). The optimisation of plant layouts with regard to energy consumption was then further discussed with regard to its environmental and economic consequences.

The challenge now, is the integration of exergo-economic approaches and the optimal reuse of materials, e.g. VOCs (volatile organic compounds), inclusion into an integrated approach for process design, not only for large chemical installations, but also for smaller production processes. Moreover, not only is lowering the energy consumption the goal of the process improvement, but also efficient materials use, which leads to a multi-criteria problem if more than the calorific value of substances is taken into account. However, unlike in heat transfer, that mainly depends on temperature differences of streams, mass transfer has additional constraints to consider, like material properties or concentrations, which may influence the direct mixing of mass streams.

The simultaneous consideration of energy and mass flow aspects constitutes ''Process Integration Technology'', which aims at developing systematic approaches for identifying cost- and resource-efficient production options (Dunn and Bush, 2001; El-Halwagi, 1997; Linnhoff, 2002), and could benefit from selected approaches of Operations Research.

In this paper, the serial coating of raw chassis is investigated. In the following section the pinch analysis approach and its formulation as a transportation problem is outlined, followed by an application of the developed methodology to surface treatment in the automotive industry in Section 3. Section 4 discusses the consequences of integrated technique assessment.

2. Systematic approach to optimisation of energy and material flows

2.1. The pinch analysis approach

For the assessment and optimisation of process systems with an exergo-economic approach, promising work has been done in recent decades (Tsatsaronis et al., 1990). Much of this work (Linnhoff et al., 1979; Linnhoff and Turner, 1981; Zhang et al., 2000) leads to a formalised integrated approach considering energy and mass flows instead of investigating single energy-conversion processes (for instance heat exchangers) independently. In chemical processes heat is utilised for the operation of reactors and the subsequent thermal separation of the reaction products. The starting point of the pinch point approach was the objective to achieve optimal energy utilisation in a process by interconnecting material flows requiring heating (so called cold flows, requiring increase of enthalpy flow) with those requiring cooling (so called hot flows, requiring decrease of enthalpy flow) and therefore was originally exclusively oriented at a minimisation of heat loss. The pinch analysis is used to calculate the target figures for minimal heat expenditure with a given minimal driving temperature difference of the heat transfer, which divides the process into two distinct sub-systems at the so called "pinch point", and whose heat/energy flows can be optimally interconnected in pairs. Design layouts of the process are thereby identified and the optimum network of interchangers, heaters, coolers with respect to annual operating and capital costs can be calculated.

By approximating hot and cold streams as linear correlations, these curves can be illustrated in enthalpy-temperature diagrams (H, T) as straight lines. Since only changes of enthalpy are relevant and enthalpy has no absolute zero point, the flows can be moved horizontally in the diagram. The individual cold and hot flows are divided into temperature intervals, whose limits are chosen so that one interval boundary lies on every entry and exit temperature. In each temperature interval the individual cold and hot heat capacity flows are added and displayed together as lines in the (H, T) diagram. Fig. 1 shows a set of hypothetical streams,

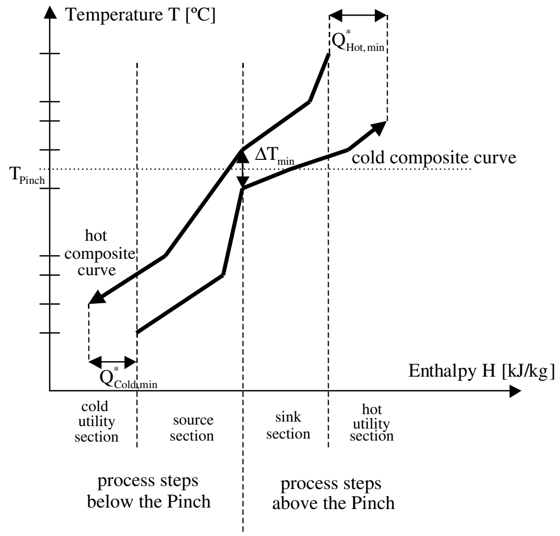

Fig. 1. Composite curves of cold and hot streams with the (H, T)-diagram (adaptal from Radgen, 1996).

each represented by a segment with constant heat capacity vs. temperature. Together they represent the entire heat balance of the system. These merged curves are referred to as the composite cooling and composite heating curves respectively. The points of discontinuity in the composite curves indicate the start or the end of one flow or the onset of a phase change (Peters et al., 2003).

In order to ensure a heat transfer between cold and hot flows, the combined curves of the hot material flows must lie over those of the cold flows in all points, and are thus moved horizontally until this condition is met. The constraint set by $\Delta T_{\min}$ is defined as the minimal temperature difference between the flows. Then the pinch point, where the distance between the hot and cold curves is minimal, denotes the possible optimal internal heat transfer between the hot and cold flows.

By decreasing $\Delta T_{\min}$ the composite curves can be shifted closer together where $\Delta T_{\min} = 0$ is the ultimate limit. $Q^*_{\text{Hot,min}}$ is the minimal amount of hot utility demanded for heating, which cannot be covered by utilising the hot flows, whereas $Q^*_{\text{Cold,min}}$ represents the amount of heat which must be dissipated by external coolers.

The process streams on the right side of the (H, T)-diagram above the pinch temperature require heating (these streams constitute the *heat sink*), whereas the process streams below the pinch temperature would need cooling (these streams are referred to as the *heat source*). Additional heating of $Q^*_{\text{Hot,min}}$ would lead to additional cooling of $Q^*_{\text{Cold,min}}$ at the end of the process steps. This would be an indication of suboptimal energy use or mismatched energy demand.

A surplus of heat below the pinch point cannot be balanced with heat demand above the pinch, since energy would have to be transferred against the temperature gradient. Incorporating these insights, three rules valid for any pinch problem can be identified (e.g. see Radgen, 1996; Dunn and Bush, 2001; Linnhoff et al., 1979; Linnhoff and Turner, 1981; Peters et al., 2003):

- no heat dissipation above the pinch,
- no heat supply below the pinch,
- no heat transport across the pinch.

The matching of hot and cold process streams can be done graphically by plotting the composite curves or by using optimisation algorithms. One approach is the use of the transportation algorithm described in the next section.

2.2. Pinch analysis as a transportation problem

The pinch problem can be solved graphically or with computer based software, e.g. flow-sheeting-tools such as ASPEN Plus (AspenTech), DIVA (Max Planck Institute for Dynamics of Complex Technical Systems) or PROII (SimSci-Esscor—Invensys) which already include algorithms for the pinch analysis with a repertoire of different heat exchangers. By linearising the hot and cold flows, the transformation of the pinch problem into an automated solving procedure as a transportation problem from Operations Research can be demonstrated (Cerda et al., 1983), where efficient algorithms exist for solving the "minimal energy input"-optimisation problem. The objective function of the general minimisation equation of transportation problems is stated in Eq. (1).

$$\min_{x_{ij}} \sum_i \sum_j c_{ij} \cdot x_{ij}, \tag{1}$$

where the parameter c_{ij} indicates the costs per unit transported material from production site i to customer j and x_{ij} denotes the transported quantity. Analogous to this, the extended objective function as the minimum utility problem can be stated as follows:

$$\min_{q_{ik,jl}} \sum_{i=1}^{C} \sum_{k=1}^{L} \sum_{j=1}^{H} \sum_{l=1}^{L} C_{ik,jl} \cdot q_{ik,jl}. \tag{2}$$

The variable $q_{ik,jl}$ (heat transferred) corresponds to x_{ij} (material transported). The transport prices c_{ij} per unit transported material are translated to the parameter $C_{ik,jl}$, which defines the possible exchanges by weighting possible process flow combinations with zero, utility consumption with one, and impossible combinations with an infinitely high value (see Eq. (3)).

$$C_{ik,jl} = \begin{cases} 0 & \text{for } i \text{ and } j \text{ are both process streams} \\ & \quad \text{and match is allowed, i.e. } k \leqslant l, \\ 0 & \text{for } i \text{ and } j \text{ are both utility streams} \\ & \quad (i = C, j = H), \\ 1 & \text{only } i \text{ or } j \text{ is a utility stream,} \\ M & \text{otherwise, where } M \text{ is a very large} \\ & \quad \text{(infinite) number.} \end{cases} \tag{3}$$

With the linear approximation of all process streams within each temperature interval, the composite curves are a combination of straight lines aggregated from the different streams in the intervals k and l (k, $l \in L$) for all cold streams i ($i \in C$) and all hot streams j ($j \in H$). (Cerda et al., 1983) prove that only corner points (points where at least one of the composite curves changes its slope) and end points can be potential pinch points. These are the boundaries of the different intervals k and l of L. In a preceding step, a set of viable pinch points can be identified, in general reducing the size of the initial problem significantly. Since only points with a change in the slope of the composite curves can be candidate pinch points, intervals without any change neither in the mass flow rate nor the heat capacity can be merged. The distinction is even more precise because points on the cold composite curve are only candidates if the slope becomes flatter at this point, whereas points on the hot composite curve are only candidates if the slope is steeper above the point.

The objective function (2) is accompanied by a series of constraints and assumptions:

$$\sum_{j=1}^{H}\sum_{l=1}^{L} q_{ik,jl} = a_{ik} \quad i = 1,2,\ldots,C,\ \ k = 1,2,\ldots,L, \tag{4}$$

$$\sum_{i=1}^{C}\sum_{k=1}^{L} q_{ik,jl} = b_{jl} \quad j = 1,2,\ldots,H,\ \ l = 1,2,\ldots,L, \tag{5}$$

$$q_{ik,jl} \geqslant 0 \quad \text{for all } i,j,k \text{ and } l, \tag{6}$$

$$a_{C1} \geqslant \sum_{j=1}^{H-1}\sum_{l=1}^{L} b_{jl}, \tag{7}$$

$$b_{HL} \geqslant \sum_{i=1}^{C-1}\sum_{k=1}^{L} a_{ik}, \tag{8}$$

with

- a_{ik} thermal energy flow in temperature interval k required by cold stream i
- b_{jl} thermal energy flow in temperature interval l to be removed from hot stream j
- C cold utility stream
- $C-1$ number of cold process streams
- H hot utility stream
- $H-1$ number of hot process streams
- L number of intervals
- c_{ik} cold process stream i in temperature interval k
- h_{jl} hot process stream j in temperature interval l
- $C_{ik,jl}$ cost of transferring a single unit of heat from heat source h_{jl} to heat sink c_{ik}
- $q_{ik,jl}$ thermal energy transferred from source h_{jl} to heat sink c_{ik}
- T temperature

Eq. (4) for example states that the heat required by cold stream i in interval k must be transferred from any hot stream. In the same manner, Eq. (5) states that the cooling of hot stream j in interval l must come from any cold stream. This transferred heat must be nonnegative (Eq. (6)), which ensures that there is no heat moving from a cold stream to a hot stream. Furthermore, there is the assumption that there is enough cooling (Eq. (7)) and enough heating capacity (Eq. (8)) of the utility streams to satisfy all cooling and heating requirements. Additionally, the problem stated assumes a given minimum $\Delta T_{\min}$ driving force, implicitly given in the required heat a_{ik} and the available heat b_{ij} per interval k and l respectively.

Furthermore, constraints can be chosen in such a way, that certain energy flow combinations are excluded, e.g. due to distances from sources to sinks that are too large (for an in-depth description of the application of the transport algorithm to the pinch point analysis see (Cerda et al., 1983)). Moreover, apart from the target function "minimal energy input" a minimisation of the costs can also be achieved.

3. Application to serial coating of passenger cars

Surface treatment technologies using solvents, such as the serial coating of cars, can cause a substantial environmental hazard due to the generation of volatile organic compounds (VOCs) and their neurotoxic properties. After their release into the atmosphere, VOCs are subject to photochemical reactions in the presence of nitrogen oxides (NO_x) and sunlight, leading to the formation of photo-oxidants. Besides PAN (peroxyacetyl nitrate) and aldehydes, the leading photo-oxidant is tropospheric ozone which primarily causes photochemical smog (so called "summer smog"). Moreover, VOCs as neurotoxins have a negative effect on health and also on vegetation.

Therefore, the European Solvent Directive 1999/13/EC sets VOC emission threshold values—inter alia—for the serial coating of passenger cars. Reduction of VOC emissions can be achieved through integrated process measures, such as the use of waterborne coatings with a lower VOC content, or by more efficient flue gas cleaning, through the determination of BAT according to the IPPC-Directive 1996/61/EC (Rentz et al., 2003).

Basically, a trade-off between reduced VOC-input and energy consumption can be observed.

Consequently, the drying process after coating the car body is central to the application of the pinch analysis and the setting of minimal cost and energy targets. In the next sections the technical background and the derived model are illustrated more precisely. Firstly, the serial coating of passenger cars is outlined, before the drying process is introduced in more detail. These conditions are mapped in the model, which is introduced and optimised in the latter part of this section. In the case study, the energy and VOC consumption of the different process steps are analysed and trade-offs are shown.

3.1. Serial coating of passenger cars

Since the appearance of a car is of major concern to customers, great importance is attached to the coating process in the automotive industry. The application of high quality coating is also important for protecting the car from corrosion, chemical deterioration, weathering, chipping etc., and for maintaining optimal optical characteristics as well as faultless and even application. Consequently, surface treatment technologies in the automotive industry are innovative: driven to a high standard of quality by customers on the one side and to a high environmental standard by the IPPC directive on the other.

Therefore, the following layer composition is widely established in Europe: (1) pre-treatment (cleaning, phosphatisation, passivation); (2) cathodic immersion prime coating (KTL); (3) underbody protection/seam sealing; (4) filler application; (5) top coat application; (6) cavity conservation and if necessary conservation for transport. In the top coat process step, apart from single layer also double layer compositions (base coat and clear coat) are applied.

These requirements lead to the application of at least three coordinated coating layers (cf. Fig. 2). After each coating application, forced drying is necessary, thus requiring energy input and generating solvent emissions.

3.2. Description of the drying process

Although there are differences in coating and their dedicated drying processes between different factories (even within the same company), a common pattern exists. In Germany double-layer top coats with a base and clear coat instead of single-layer coats are applied almost exclusively (Rentz et al., 2003).

The major environmental impacts during the drying process are caused by energy consumption and volatile organic compound emissions from solvents in the coating material. The drying process consists of three independent drying tunnels: The drying tunnel for the cathodic immersion prime coating (KTL) with temperatures of around 180 °C, the drying tunnel for the filler application at around 165 °C and the drying tunnel for the top coat with typical temperatures around 140 °C (cf. Fig. 3). These temperatures are mean values and not values of a specific coating material. Moreover, these are the temperatures of the zone where one temperature level is retained for most of the time and does not consider the warm-up at the beginning of the drying tunnel.

The assembly line carries the chassis through the drying tunnels and leads to drying times of 50 minutes in the oven after cathodic immersion of the prime coating, 30 minutes in the filler oven and almost 40 minutes in the top coat oven.

The flue gas flow depends on the length of the drying tunnel, the number of filters (flue gas stream per filter is constant) and further technical process requirements. In general there are flue gas streams between 8000 and 15,000 Nm^3/h.

These three drying tunnels use three independent thermal incineration facilities. Thermal incineration is a proven technology, which offers a safe, reliable, and efficient method for the removal of a wide range of VOCs (except halogenated hydrocarbons). They undergo oxidation in a combustion chamber at temperatures between 700 and 1000 °C, to a certain extent with the addition of fuel. Removal efficiencies up to 99% and even above can be achieved. A basic flowsheet is given in Fig. 4.

Delays resulting from malfunctions and downtimes in the production facilities cause an automated shutdown of the heating in the drying tunnels and an ensuing cooling down of these. Increased energy consumption due to these down-

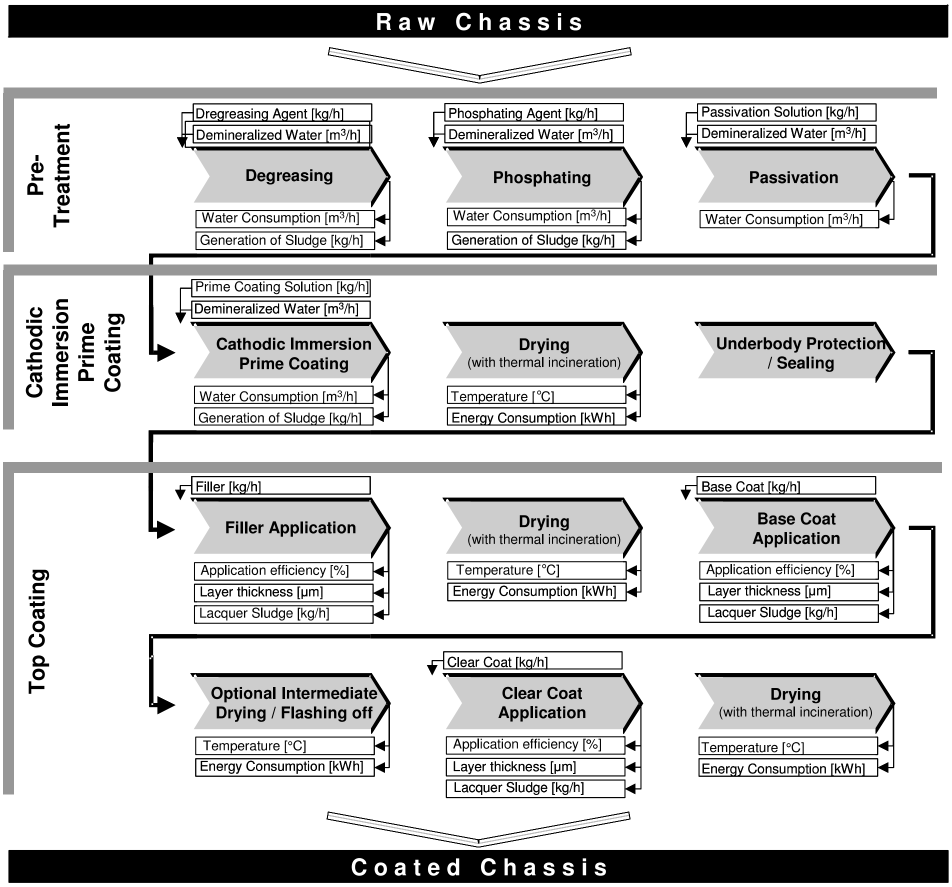

Fig. 2. Flowsheet of serial coating of passenger cars (Rentz et al., 2003).

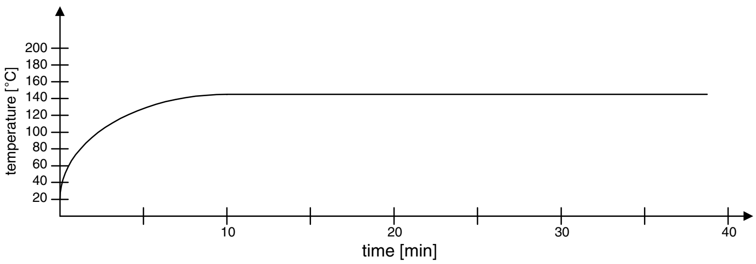

Fig. 3. Run of the temperature curve in the top coat oven.

times, which might be substantial, is not considered in the following model.

3.3. Description of the model

The derived model maps the three drying process steps and considers their different temperature requirements. The three former independent drying process steps are mapped as a network. Interconnections between the air streams are considered from the top coat drying process with high demand for drying air, to the filler and the prime coating drying processes with relatively lower requirements. These flows are illustrated in

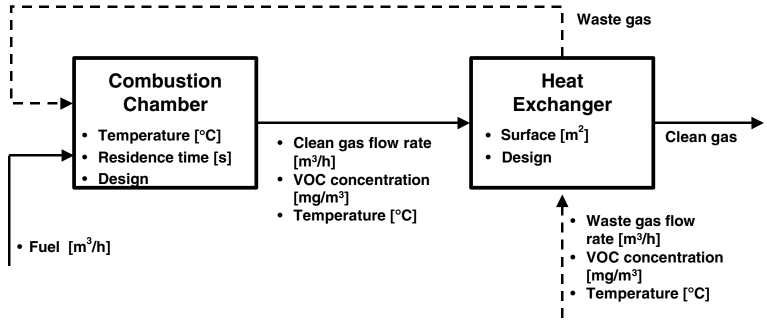

Fig. 4. General scheme of the thermal incineration process with relevant parameters.

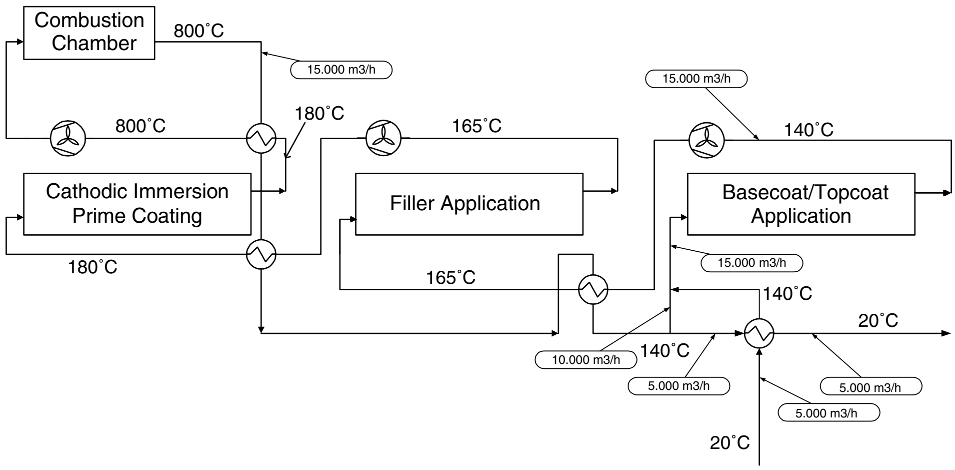

Fig. 5. Model of the drying processes.[1]

Fig. 5. Air, which comes from the top-coat application, can be used in the drying tunnel of the filler application and then in the drying tunnel of the cathodic immersion coating. Inlet and outlet temperatures are the constraints put on the different flow connections. Fig. 5 only illustrates the cold and hot process streams and not the utility flows.

The minimum difference of the driving temperature of the heat exchanger network is set to 10 °C. This leads to the possible pinch temperatures of the inlet and outlet temperatures plus the projected temperatures 10 °C below or above these (cf. Table 1).

The temperature intervals start with the required cooling enthalpy at the lowest temperature ($-\infty$ to 20 °C) and end with the required heating enthalpy at the highest temperature. Since there is no VOC present in the hot process streams, these streams have not been projected, because the slope of the hot composite curve would not change at these points. Furthermore, a supply of 5000 m^3/h of fresh air is assumed.

Toluene is assumed to be the solvent used in the coating process.[2] Since the boiling point of toluene is at 110.6 °C, only the heat capacity of the gas phase needs to be considered and no phase changes occur in the considered exchanger system (cooling the hot streams down from 800 °C to 20 °C is irrelevant in this case since the air has been purified and is thus solvent free). The heat

[1] Symbols according to DIN Norm 28004

[2] Toluene is one of a broad variety of solvents used in industrial applications.

Table 1
Temperature intervals

Interval	Cold process streams		Hot process streams	
	Inlet T [°C]	Outlet T [°C]	Inlet T [°C]	Outlet T [°C]
1	$-\infty$	20	20	30
2	20	140	30	150
3	140	165	150	175
4	165	180	175	190
5	180	790	190	800
6	790	800	800	$+\infty$

capacity of toluene for each temperature is calculated using the temperature taken in the middle of the considered temperature intervals and by approximating it as an ideal gas (cf. Table 2).

In order to minimise resource use and thus costs, the aim is to calculate the minimum utility needed to supply all of the required heating and cooling duties of the process. This minimum is the target for utility consumption. The inlet and outlet temperatures of all flows are given and a linear dependency is assumed as the product of a given flow rate and a given specific heating capacity and density.

An oxygen percentage of 21% and a nitrogen percentage of 79% is assumed for the drying air, and toluene accumulates in the air throughout the drying process. The concentration of toluene at the different temperatures in the drying air determines the heat capacity of the air stream to be heated.

On average, 3 kg of solvents are used per car (0.5 kg for the immersion prime coating, 1.2 kg for the filler application and 1.3 kg for the top coat application) and assuming a large production facility with approximately 138,000 cars per year, a solvent consumption of 90 kg solvents per hour is derived (Rentz et al., 2003). The pure drying air therefore contains on average 39 kg/h of toluene from the immersion prime coating, 75 kg/h from immersion prime coating and filler application and 90 kg/h after the top coating process. With these concentrations and the heat capacities of toluene at the different stages and temperature levels, the overall heat capacities of the streams can be calculated (cf. Table 3). The air stream to be cooled contains no solvents at all. Therefore, the heat capacity of this air stream is assumed to be 1.01 kJ/kg K over the whole temperature range. The density [kg/m^3] of the air streams is assumed to be similar to an ideal gas with an average pressure (1013.25 hPa) and varies with temperature.

Table 2
Heat capacity of toluene with approximation to an ideal gas and average value for the temperature intervals

Interval	Temperature [°C]	Temperature [K]	C_p [kJ/(kg K)]
3	150	423.15	1.50
4	170	443.15	1.63
5 and 6	480	753.15	2.50

These findings are summarised in Table 3, which shows the temperature intervals, the corresponding heat capacity, density, flow rate, temperature change and finally the enthalpy difference.

With these data the enthalpy changes in the temperature intervals can be calculated and a temperature vs. enthalpy diagram can be drawn (cf. Fig. 6). Fig. 6 shows the cold and the hot composite curves for the drying processes. The curves run almost parallel due to the small changes in the heat capacity.

These results are the input data for the transportation model, where the enthalpy difference is interpreted as the required or the available heating and cooling in each interval. These are the assumptions for the mapped model, which are used in the next section to obtain design implications for the process layout planning.

3.4. Results of the calculations

The calculations were carried out with the linear optimisation software GAMS (GAMS Development Corporation) within a transportation module as described in Section 2.2. The total required

Table 3
Temperature intervals and enthalpy changes within the process

Inlet *T* [°C]	Outlet *T* [°C]	C_p [kJ/(kg K]	Density [kg/m^3]	Flow rate [m^3/h]	Temperature difference [°C]	Enthalpy difference [kJ/h]
Cold process streams						
$-\infty$	20	1.010	1.247	5000	0	0
20	140	1.010	1.000	5000	120	605,826
140	165	1.011	0.834	15,000	25	316,317
165	180	1.013	0.793	15,000	15	180,767
180	790	1.019	0.469	15,000	610	4,370,675
790	800	1.019	0.331	15,000	10	50,521
Hot process streams						
30	20	1.010	1.184	5000	10	59,799
150	30	1.010	0.972	5000	120	589,144
175	150	1.010	0.811	15,000	25	307,290
190	175	1.010	0.775	15,000	15	176,079
800	190	1.010	0.460	15,000	610	4,247,478
$+\infty$	800	1.010	0.327	15,000	0	0

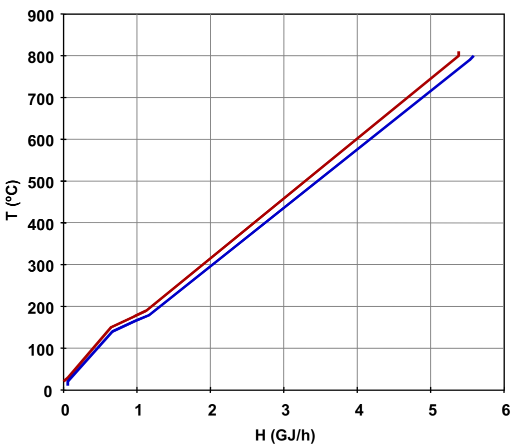

Fig. 6. Composite curves of the cold curve and the hot.

energy for cooling and heating is 263,914 kJ/h and results in a pinch point at a temperature of 20 °C for the cold flows and 30 °C for the hot flows at the bottom of the composite curves. The required additional enthalpy is determined by adding the additional heating for various streams 204,115 kJ/h with cooling at the coldest process stream, where no internal process stream is available 59,799 kJ. Table 4 shows the interconnection between the different process streams and the utilities.

These results imply that connection of the different drying tunnels and modelling of the different flows deliver a good insight into the serial coating of raw chassis. Heat is not only transferred within each drying tunnel, but also between the different drying tunnels.

Table 4
Heat-transfer-table

Interval		Hot process streams						Hot utility	Sum
		1	2	3	4	5	6		
Cold process streams	1								0
	2		589,144	16,682					605,826
	3			290,608				25,709	316,317
	4				176,079			4688	180,767
	5					4,247,478		123,197	4,370,675
	6							50,521	50,521
Cold utility		59,799							**59,799**
Sum		59,799	589,144	307,290	176,079	4,247,478	0	**204,115**	**263,914**

Since the separation of VOC from waste gases is usually carried out via thermal condensation, as described in this case study, the pinch analysis can also be implemented on waste gases containing VOC, as this case study demonstrates, or multi-component VOC (see also Dunn and El-Halwagi, 1994; Dunn and Bush, 2001; Parthasarathy and El-Halwagi, 2000). Thus the reclamation of organic solvents can be translated to a problem of heat exchanger networks. This approach opens the path to further integrated process enhancements, but will also lead to trade-offs between the different objectives and to a multi-criteria problem. It becomes obvious, that not only the chemical properties of VOC-emissions (causing photochemical oxidant formation), but also their calorific value is of interest in process optimisation. A trade-off between reduced VOC-content in paints and increased energy consumption for the drying process should be taken into consideration.

4. Discussion

With the advent of more advanced process models and computational power, process integration technologies gain in importance. Various process layout options can be investigated by help of unit operations modelling mass and energy flows in parallel. Likewise, the scope of the process model can be enhanced gradually retaining a manageable level of computational complexity.

The advantage of the pinch analysis can be seen in the determination of the theoretical optimum for a given set of heat and material streams.

Zhelev and Semkov (2004) state that pinch analysis has a little different process modelling approach to classical unit operation modelling—it looks for firm constraints to deliver design guidelines. Based on these constraints an idealised maximum of heat and mass transfer is to be set and accepted as the so-called target for future design.

In the approaches of the pinch analyses discussed so far, however, only single energy and material flows were regarded. Even the "Multi-component-VOC-Strategies" (Dunn and El-Halwagi, 1994) had only one target figure in Operations Research terms, in which the process design was formulated as a MINLP-Problem (mixed-integer non-linear program) for the minimisation of the total average annual costs (annuity method) of the company's internal network; the boundary conditions being material and heat balances, and economics, environment and thermodynamics being the constraints (Chen et al., 2004).

Especially an inter-enterprise application of process integration technologies may lead to significant savings in energy and raw material consumption, if certain preconditions are fulfilled (such as short distances between plants or the possibility of storing material in buffer tanks). Then, target values other than those originally sought (e.g. VOC recovery), such as the optimisation of energy consumption and water conservation can come to light. Through the parallel reduction of water use, energy consumption and VOC emissions, a multi-criteria process design problem for company-wide facility planning must be solved, in order to implement efficient recycling cascades. Resulting conflicting solutions must be evaluated based on a multi-criteria approach. For this purpose the following procedure is suggested:

1. Pinch analysis for the optimal interlinking of heat flows with heat exchangers.
2. Mass pinch analysis for waste disposal or related material flows, in order to minimise material use and waste production.
3. Water pinch analysis.
4. If there is no overlap between the pinch analyses in the process design, all identified recycling cascades can be realised at once.
5. If overlaps occur, multi-criteria decision support algorithms can be used to derive a prioritisation. For this purpose convenient OR models (for instance the Outranking method PROMETHEE, Brans et al., 1986; Geldermann and Rentz, 2001) can be employed and modified, this requires further research.

The requirements for the implementation of the proposed method are measurable indicators of material and energy flow, e.g. temperature, COD[3] requirements, VOC concentration or efficiency. Thanks to breakthroughs in molecular modelling, scientific instrumentation, related signal processing and powerful computational tools, in the near future massive progress is expected in chemical engineering, which allows for a ''multi-scale and multi-disciplinary computational chemical engineering modelling and simulation of real life situations'' throughout the entire supply chain, beginning at the molecular level and aggregating in subsequent steps to the process level (Charpentier, 2002). In addition, this will also introduce new possibilities for cleaner technologies and environmental protection by optimally combining process integrated emission reduction measures and end-of-pipe technologies challenging also the research in the field of Operations Research.

5. Summary

Process optimisation, materials reuse and in particular, the optimisation of energy use have a long tradition in process engineering. Tools for integrated process design now aim at a holistic approach to process design, retrofitting, and operations planning. In a preliminary design, cost and energy ''targets'' (i.e. the minimum possible values of these objectives) are calculated based on pinch analysis. This approach can also be applied for the optimisation of drying processes, as the presented case study from serial automobile coating shows. The derived model maps the three drying process steps while considering their different temperature requirements as a network.

From a methodological point of view, the pinch analysis can be formulated as a classical transportation problem in Operations Research terms. Important for an appropriate mapping of the plant to be examined, is the detailed consideration of the technical requirements of the underlying processes. If more than one target (such as energy) is regarded, or an inter-enterprise application concerns a larger network, the consideration of all possible interconnections, however, easily leads to a combinatorial problem, requiring appropriate OR algorithms.

It can be concluded that the pinch analysis, combining economic and ecological aspects with a multi-disciplinary approach, makes eco-efficiency operational. In combination with appropriate Operations Research methods, new insights into plant layout planning and emission reduction measures can be achieved.

[3] Chemical oxygen demand.

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