INTEGRATED UNIT LOAD AND TRANSPORT SYSTEM DESIGN IN MANUFACTURING

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Keywords: Unit load design, material handling costs.

Abstract

This paper addresses the selection, evaluation and specification of material transport technology in agile job shop manufacturing. Specifically an integrated approach to design unit loads concurrently with appropriate material transport vehicles is investigated in the following steps:

1. Systems boundary definition and collection about the goods handled and the required material transport tasks.
2. Task allocation to available resources and technologies.
3. Evaluation and selection of unit load alternatives and material handling and transport equipment.

Material handling device evaluation is based upon a conventional multicriteria decision–making approach. Decision criteria are developed from agile manufacturing requirements according to logistic needs for internal and external transportation and alternative solutions are evaluated for two design options. The improvements made in terms of flexibility, adaptability to different goods handled, better space utilization, simplification and acceleration of in-plant transportation are demonstrated in a case study for steel frame manufacturing.

1 Introduction and literature review

Agile manufacturing has been viewed from a wide perspective with various taxonomics of strategic and technological issues (Gunasekaran 1998 [5] and 2002 [6], Sanchez e.a. 2001 [9]). These issues are based upon general principles like customer satisfaction, ongoing change management, integrating human skills and endeavor to form partnerships. Transforming them into operational goals on the factory level means facing rapidly changing markets, decreasing product time to market, local and global sourcing and distribution. Another trend is the increasing virtualization in all phases of the product life cycle.

This means an integrated approach during product design is needed for manufacture, assembly, ergonomics, reliability and cost. In facilities design value adding processes are closely connected with material handling and storage systems specification.

Agile manufacturing systems require adaptable and flexible material transportation and intermediate storage systems to meet frequent and quick market changes (Sanchez, Nagi 2001 [9]). To support the planning process of these systems performance measures were developed (Beamon 1998 [2]) to evaluate material handling systems, but no design rules for improving flexibility, reliability and performability have been developed there. The material handling equipment selection procedure has been improved by a computer-aided MHE selection system called ADVISOR (Chu, Egbelu, e.a. 1995 [3]). It can be considered as a valuable design tool, but it still depends on user skills reflecting his/her planning experience and decision capabilities. Also the economic analysis module analyses the costs of each equipment type, but does not give overall results including unit loads.

An interesting approach has been investigated in the work of Vondran, 2001 [10]) and a similar method of Welgama, 1996 [11]. They consider layout optimization jointly with material handling equipment selection assuming that neither the layout nor handling methods are determined in advance. Both integrate cost aspects and construct a layout with minimum space and distance requirements. Their differences are a slightly different approach in cost determination and in the layout construction procedure. Also Vondran, 2001 [10] considers transportation costs per distance thus impeding the conventional approach in equipment costs per hour. On the other hand Welgama e.a., 1996 [11] does not consider unit load cost and design effects in depth. Thus it is the intention of this paper to consider the effect of unit load design on material handling equipment and cost evaluation in an agile manufacturing environment.

2 Material handling equipment selection

Material handling systems determine to a major extent the costs and competitiveners of products. A complete analysis is required to select appropriate material handling equipment and to assign individual moves to the individual items during their flow through a production network. Layout design and equipment selection exhibit mutual dependency. However only in rare cases of new factories a new layout design can be optimized jointly with the material handling system design.

In most real life conditions the layout is determined by the manufacturing process and cannot be changed easily. Thus

the location of the value adding manufacturing procedures determine the transportation network within a factory.
A weakness of most material handling equipment selection methods is, that the loads to be moved are considered as given. At least as much attention should however be paid to the unit load formation task. This needs to address not only determining the unit load type and size, but also carefully considering the loading and unloading processes. These can be executed manually and semi- or fully automated and include the selection of appropriate grippers or other mechanical devices to pick up, orient and deposit the items onto the unit load under consideration.

3 Unit load design

Both Egbelu e.a., 1995 [3] and Apple, 1972 [1] consider the influence of the load type, material, weight, dimensions and application for the unit load selection process. Unfortunately no information is available on knowledge base rules to select devices for leading and unloading the unit load with individual items or workpieces, which clearly influences the type and design of feasible unit loads. As a tremendous variety of items from small to large or lengthy shapes needs to be considered we restrict ourselves in this case to metal-sheet transportation and intermediate storage with lengthy and irregular shaped sheets.
These sheets are needed to manufacture steel frame constructions used in heavy machining equipment. Due to cost restrictions premanufacturing of sheets is often executed by outside vendors and the material delivered through an external logistics process (Figure 1). Outsourcing and vendor cooperation classify this solution as agile manufacturing activity.

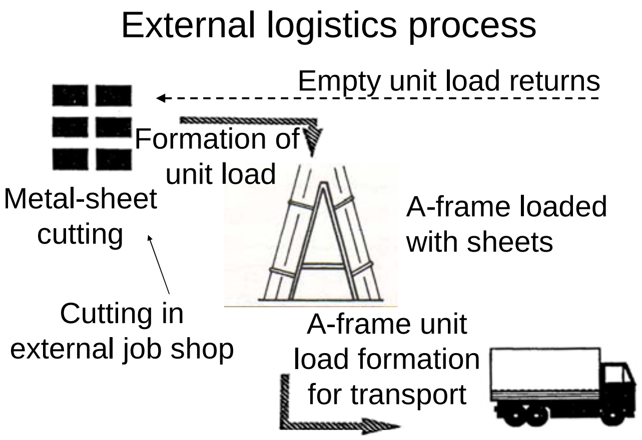

Figure 1: External logistics.

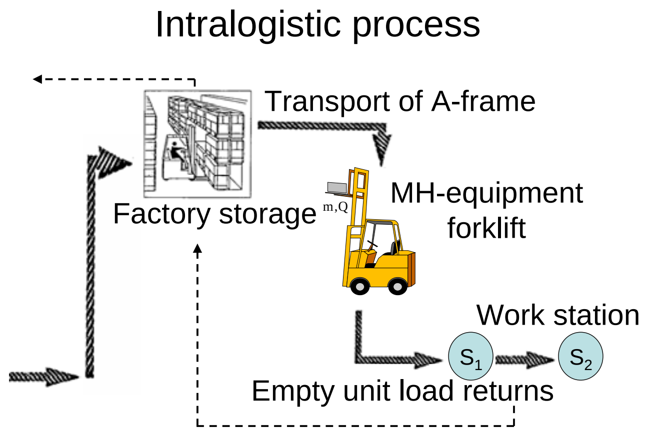

Figure 2: Intralogistics.

In the past individual sheets were loaded together on standardized pallets and delivered to the factory in a common storage facility. Despite of load securing devices the lengthy parts extended the pallet's longitudinal dimension (Figure 3) and damages occurred often times.

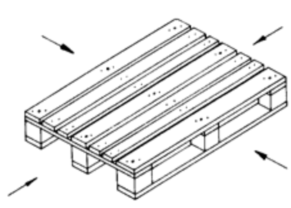

Figure 3: Pallet unit load.

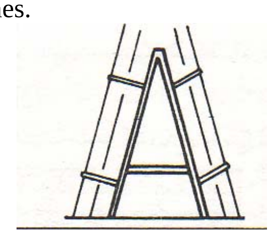

Figure 4: A-frame portable rack.

Therefore a solution was developed to avoid damage, secure the items and improve the intralogistic process by transporting the same unit load shaped as an A-frame (Figure 4) from the facility storage to the first workstation S1. The unit load is not only capable of carrying the lengthy items but has also extra compartments to carry small parts like ribs. By proper unit load design all parts belonging to a certain lot size of a finished product can be carried on one special purpose A-frame instead on several pallets needing several moves of transportation. After unloading individual metal-sheets are positioned in welding fixtures for further operation. The empty A-frames are stackable and transported as collective unit load back to the factory storage and the outside vendor. Clearly the design of an A-frame as dedicated portable storage rack for multiple item loading is more complicated and costly than a general purpose pallet. Thus system performance and transportation costs need to be compared for the two solutions. This can be done by modelling the manufacturing facility as a stochastic queuing model to capture dynamic effects in processing variability (Oser, 2006 [7]). However in this case it was decided that an integrated static capacity and cost model would be sufficient to evaluate the two solutions. This is presented in the next section.

4 Material handling cost model

This model is based to a large extent on the work of Vondran, 2001 [10]. In the cost model we changed from a distance to a time based cost evaluation. A conventional expression to estimate total material flow effort is given by

$$K = \sum_{i=1}^{n}\sum_{j=1}^{n} m_{i,j} d_{i,j} \qquad (1)$$

with

K total transportation effort from multiplying flow intensity with distance

n number of stations visited

$m_{i,j}$ number of loads per time unit transported between station i and j

$d_{i,j}$ distance between station i and j

This model does, however, not represent actual cost calculations and is therefore extended to the following equation.

The next formula calculates transportation costs per time

$$k_{ij} = \sum_{t=1}^{q}(k_t + k_p)x_{ijt} \ \text{ with } 1 \le q \le F \ \left[\frac{€}{\text{hour MHE}}\right] \qquad (2)$$

with

k_{ij} transportation costs between stations i and j

q number of all possible MH equipments feasible for the transport between stations i and j

k_t cost rate in €/hour for each MH equipment

k_p cost rate in €/hour for one unit load

x_{ijt} number of individual transports executed with MH equipment t

F number of stations located in layout

t index of material handling equipment

p index of unit load

k_h hourly cost rate for energy consumption, maintenance and repair or rentals

$$K = \sum_{i=1}^{n}\sum_{j=1}^{n} t_{i,j}\left(\sum_{t=1}^{q}(k_t + k_p)x_{ijt}\right) \ \text{ with } i \ne j \text{ and } 1 \le q \le F \qquad (3)$$

with

K total costs of transportation for c_{aij} items in €

$t_{i,j}$ travel time between stations i and j

n number of stations visited

k is the hourly cost rate of equipment t and p, respectively, and can be calculated from a simple expression

$$k = \frac{I}{mz} + \frac{Ir}{2z} + k_h \qquad (4)$$

with

I investment costs in €

m number of years in operation

z number of operational hours per year

r yearly interest rate

Considering unit load formation and empty travel the number of transports executed is

$$x_{ij} = \sum_{a=1}^{u}\frac{c_{aij}}{h_{ap}b_{tp}} + l_{ijt} \ \text{ with } u,p \ge 0 \qquad (5)$$

with

x_{ij} number of transports executed

u number of different workpieces or items

c_{aij} number of individual items “a” transported between stations i and j

h_{ap} loading factor $h_{12} = 40$ means forty items #1 loaded in unit load #2

b_{tp} unit load factor $b_{12} = 5$ means five unit loads type 2 can be transported simultaneously on MH equipment # 1

l_{ijt} number of empty travel transports with MH equipment t between stations i and j

A basic assumption is that each SKU is allocated to only one unit load type and that the MH equipment is fully utilized. Further substitution results in

$$K = \sum_{i=1}^{n}\sum_{j=1}^{n} t_{ij}\left(\sum_{t=1}^{q}(k_t + k_p)\left(\sum_{a=1}^{u}\frac{c_{aij}}{h_{ap}b_{tp}} + l_{ijt}\right)\right) \qquad (6)$$

$$\text{with } i \ne j,\ 1 \le q \le F \ \text{ und } u,p \le 0$$

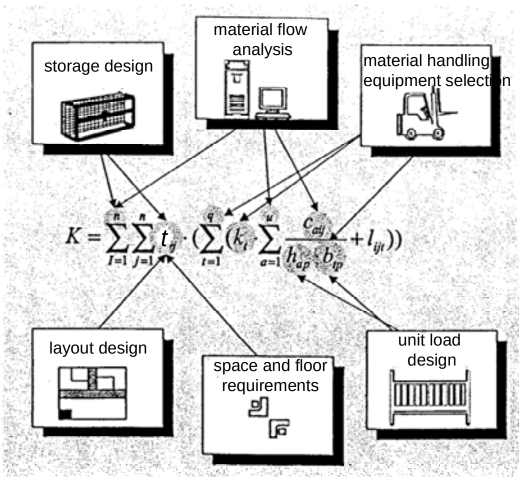

Figure 5: Integrated material handling costs (Vondran, 2001).

In summary Figure 5 shows according to Vondran [10] the integrated influence on MHE-costs from storage design, material flow analysis, MH equipment selection, layout design, space and floor requirements and unit load design.

5 Operation time calculation of cranes and industrial vehicles

Total travel time t_{ij} for intermittent operation of discontinous MH equipment is calculated from

$$t_{i,j} = t_A + t_b + t_E + t_l \qquad (7)$$

Total operation time t_{ijbl} of bridge and gantry cranes can be calculated from adding sequential moves for lifting H, travelling k_r, k_a and lowering S sections during a total cycle $t_{i,j}$ with s (m) as distance, v (m/s) velocity, n as number of sections and a as acceleration “a” and deceleration “v”.

Crane cycle time calculation is according to Fischer, 1981 [4] possible with

$$t_{i,j,B,l} = \frac{s_H}{v_H} + \frac{n_H v_H}{2}\left(\frac{1}{a_{Ha}} + \frac{1}{a_{Hv}}\right) + $$
$$+ \max\left\{\begin{matrix} \frac{s_{Kr}}{v_{Kr}} + \frac{v_{Kr} n_{Kr}}{2}\left(\frac{1}{a_{Kra}} + \frac{1}{a_{Krv}}\right) \\ \frac{s_{Ka}}{v_{Ka}} + \frac{v_{Ka} n_{Ka}}{2}\left(\frac{1}{a_{Kaa}} + \frac{1}{a_{Kav}}\right) \end{matrix}\right\} + \quad (8)$$
$$+ \frac{s_s}{v_s} + \frac{n_s v_s}{2}\left(\frac{1}{a_{Sa}} + \frac{1}{a_{Sv}}\right)$$

The operation cycle time of industrial vehicles travelling through n curves on their path is calculated from

$$t_{i,j,B,L} = \frac{s_t}{v} + n_K\left[\frac{v}{a}(1-n_v)^2 + \frac{s_K}{v}\left(\frac{1}{n_v} - 1\right)\right] \quad (9)$$

with

s_t	total distance travelled
t_A	loading time
t_E	unloading time
t_B, t_L	travel time loaded, travel time empty

$$n_v = \frac{v_K}{v} = \frac{\text{curve speed}}{\text{full travel speed}} \quad (10)$$

n_K	number of curves
s_K	length of curve

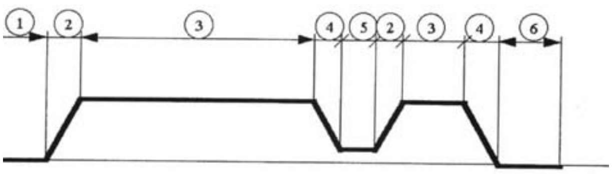

Figure 6: Travel velocity as function of time.

1. t_{pick}	loading time	[sec]
2. acc	acceleration	[m/sec²]
3. $v_{fast/slow}$	travel speed	[m/sec]
4. dec	deceleration	[m/sec²]
5. v_{Kurv}	curve speed	[m]
6. $t_{deposit}$	unloading time	[sec]

6 Example calculation

An example of metal sheet machinery equipment is shown in Figure 7 with a steel frame consisting of lift arms used in front end loaders for construction or mining work. Another application is the production of welded bogie frames for railway cars and locomotives.

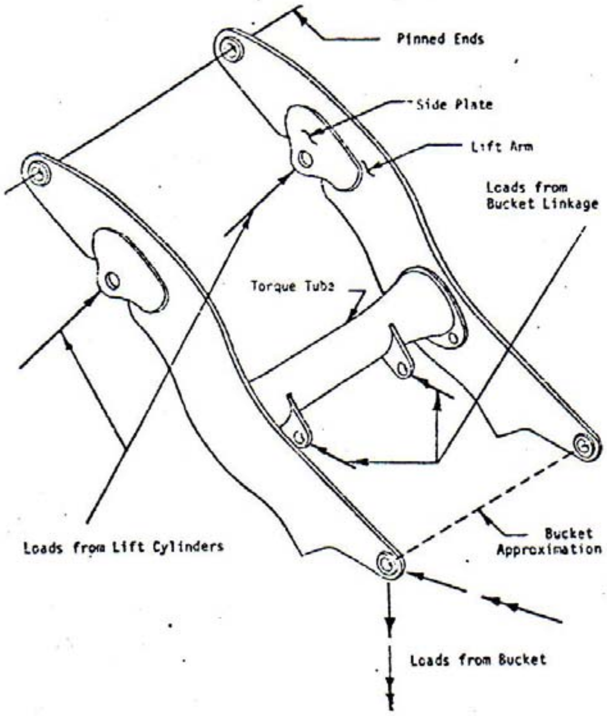

Figure 7: Heavy industry steel frame for front end loaders.

Typically, sheet metal parts are produced from raw material by a number of cutting and bending operations. Steel frame production is used as an example for calculation fork lift truck travel and A-frame unit loads with travel speed v = 1,5 m/s and an average acceleration/deceleration a = 0,75 m/s². The layout exhibits four curves with radius 3 m, curve length 4,5 m and a curve speed 0,5 m/s.

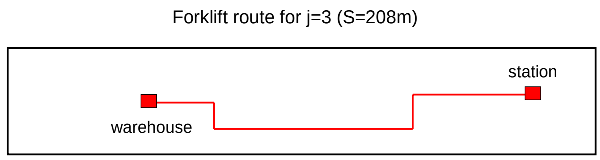

Figure 8: Example layout of forklift path.

Loaded travel time is calculated from equation (9) and assumed to be equal to unloaded travel

$$t_{01} = (208/1,5 + 4(1,5/0,75(1\text{-}1/3)^2 + 4,5/1,5(3\text{-}1) \quad (11)$$
$$t_{01} = 166,5(s)$$

Including an average loading time of 22 (s) the total trip time is t_{t1} = 188 (s).
Further calculations assume a special purpose unit load A-frame with a capacity of l_{cap} = 40 items/unit load due to weight restrictions. With one unit load per trip b_{tp} = 1 and a required lot size of c_{aij1} = 160 it/lt. the number of transports executed is from (5)

$$x_{ij1} = \frac{160}{40} + 4 = 8 \text{ trips loaded and empty back.} \quad (12)$$

Hourly costs of a 1,6 t electro fork lift truck from VDI 2695 are approximately k_{t1} = 15 €/hr and A-frame holding 40 items costs about k_{p1} = 1,2 €/hr.

The total costs of transportation for one lot is calculated from equation (3)

$$K_1 = 188/3600(15+1,2)8 = 6,77 \text{ €/lot} \quad (13)$$

Solution 2 with pallet transport can load 15 items per unit load, so the number of trips necessary becomes

$$x_{ij2} = \frac{160}{15.2} + 6 = 12 \text{ trips loaded and empty back,} \quad (14)$$

because the fork lift has a loading capacity of two pallets. However due to the lighter load a faster travel speed of 1,8 m/s is possible and with a trip time of t_{t2} = 160 (s).
Pallet costs per hour are assumed to be 0,7 €/hour and lead to total costs of

$$K_2 = 160/3600(15+0,7)12 = 8,37 \text{ €/lot.} \quad (15)$$

Despite lower pallet costs as opposed to the A-frame unit load and shorter travel times larger total costs of transportation result for the solution of pallet transportation due to more trips necessary with pallets.

7 Summary

First the dependencies between agile manufacturing and material handling issues have been developed and a literature review was presented. In the next section material handling selection and unit load design have been discussed. Next a static material handling cost model was developed and operation time of MH equipment was presented. Finally an example calculation comparing two unit load design solutions showed the applicability of the method.

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