Competitiveness of Timber Floor Elements: An Assessment of Structural Properties, Production, Costs, and Carbon Emissions

Sveinung Nesheim
Kjell Arne Malo
Nathalie Labonnote

Abstract

As long-spanning timber floor elements attempt to achieve a meaningful market share, proof of serviceability continues to be a demanding task as international consensus remains unsettled. Initiatives to improve vibration levels are achievable, but a lack of confidence in the market is resulting in increases in margins for both manufacturers and contractors. State-of-the-art concrete alternatives are offered at less than half the price, and even though timber floors offer reduced completion costs and low carbon emissions, the market is continuously reserved. Cost reductions for timber floor elements to competitive levels must be pursued throughout the product details and in the stages of manufacturing. As new wood products are introduced to the market, solution space is increased to levels that demand computerized optimization models, which require accurate expenditure predictions. To meet this challenge, a method called item-driven activity-based consumption (IDABC) has been developed and presented in this study. The method establishes an accurate relationship between product specifications and overall resource consumption linked to finished manufactured products. In addition to production time, method outcomes include cost distributions, including labor costs, and carbon emissions for both accrued materials and production-line activities. A novel approach to resource estimation linked to assembly friendliness is also presented. IDABC has been applied to a timber component and assembly line operated by a major manufacturer in Norway and demonstrates good agreement with empirical data.

Producers of timber flooring systems are endeavoring to gain a market share in commercial buildings. In this market cost is the dominant selling point, hence cost reductions for timber floor elements to competitive levels must be pursued throughout the product details and in the stages of manufacturing. However, future competitiveness is not an issue of cost only. The construction sector currently contributes 36 percent of global energy use and 39 percent of carbon emissions (UN Environment and International Energy Agency [IEA] 2017), and emission reduction targets are likely not to be met without a reduction of the energy consumption in the sector. Eighty-five percent of the buildings we will use in 2050 are currently built (Dixon et al. 2018). Still, projections indicate that 230 billion square meters of buildings will be erected or reconditioned by 2060 (IEA 2017). Estimates suggest that greenhouse gas (GHG) emissions are likely to double in the same period (Pomponi and Moncaster 2016). Material efficiency analyses have been performed to form strategies for reducing GHG by substituting steel and concrete with timber (Hertwich et al. 2019). Studies of energy-efficient buildings show a reduction of GHG in the service lifetime, but an increase in embodied GHG of the building itself (Röck et al. 2020). As political incentives are encouraging the use of environmental beneficially materials (Hill and Dibdiakova 2016), the market potential for timber elements gains strength. However, the construction industry expects more research be done to improve timber floor systems and simultaneously reduce GHG emissions and cost.

The authors are, respectively, PhD Candidate and Professor, Norwegian Univ. of Sci. and Technol., Trondheim, Norway (sveinung.nesheim@ntnu.no [corresponding author], kjell.malo@ntnu.no); and Senior Research Scientist at SINTEF, Norway (nathalie.labonnote@sintef.no). This paper was received for publication in October 2020. Article no. 20-00067.

Forest Prod. J. 71(2):111–123.
doi:10.13073/FPJ-D-20-00067

As new wood products are introduced, computerized optimization models may be required to find the optimum solution both to cost and embodied carbon emissions. Forintek and the Canadian Wood Council (Hu et al. 2006) concluded that an accurate accounting of the expenditure of manufacturing is required to formulate methods of optimization of timber floor elements.

Assessment of estimation methods for major construction cost factors provides evidence of the importance of accurate accounting (Akintoye 2000). Akintoye's (2000) study reports that construction and buildability constitute critical factors, and that precise estimates of cost and delivery of prefabricated components such as floor elements are essential.

Cost of direct material (material from supplier) and labor cost are key indicators of competitiveness, but better a description of machining processes may further enhance competitiveness (Ratnasingam et al. 1999). The study by Ratnasingam et al. (1999) brings an understanding of furniture wood machining and the related machining cost, and argues that machining costs may be calculated using activity-based costing (ABC; Drury 1992). Drury's (1992) study has many similarities to the present work, but the level of detail may not be suitable for heavy timber product manufacture. Implementation of lean manufacturing in the secondary wood industry increases competitiveness, according to (Velarde et al. 2011). Depending on the factory, lean manufacturing requires specific systems, and the implementation of new systems can be a burden for a factory. However, the outcome may reduce excess production time, and increase the efficiency of the factory floor and the utilization of direct material.

The US Department of Agriculture and the Wood Components Manufacturers Association developed a product cost quotation tool for timber component manufacturers (Andersch et al. 2013, 2014). This is a robust framework for cost accounting but is based on traditional costing methods and historical data taken from the company applying the method. It is not parametric, nor does it facilitate the calculation of carbon emissions linked to manufacturing. As such, it cannot be applied as part of an optimization algorithm without extensive redesign. Other studies have been carried out with the aim of developing methods to assist sawmill operators in estimating product costs (Howard 1988), but such methods are not representative of cost calculations used in timber element manufacturing.

An outline of basic manufacturing costing methods is presented in Moore and Creese (1990). In this study, costs are assigned to specific activities and the methods described share similarities with the frequently applied models using ABC (Yongqian et al. 2010) and time-driven ABC (TDABC; Namazi 2016). Applied for product manufacturing, the ABC methods all define activities along the production line as resources that combine to perform operations in the manufacture or processing of a given item. The drawback of these models is that they are not parameterized, and require input in the form of predetermined values of activity durations. More advanced mathematical methods are able to model demand-driven manufacturing. The method described in Kalaiarasi and Rajarathnam (2015) addresses inventories and not activities, while Durga Prasad et al. (2014) describe an approach involving a mathematical representation of quality control, value engineering, and target costs. In the latter approach, product cost management during the conceptual phase is studied as a means of balancing costs and quality, and the mathematical relationships are analyzed and solved to support optimization procedures during product development.

The manufacturing of timber-based floor elements is a machine-driven production process. The machining industry is increasingly required to record and reduce its carbon emissions. The energy consumption of timber element manufacturers is moderate compared to sectors such as the metallurgical and chemical industries, where the levels of energy consumption and carbon emissions are excessive. However, the topic still has relevance for the timber components and assembly sector. In studies by Cai et al. (2018), Hu et al. (2018), and de Souza Zanuto et al. (2019), methods to manage carbon emissions related to consumables are studied, whilst Du et al. (2015) study operational models for low-carbon manufacturing processes to assist in strategic work to reduce carbon emissions in the machinery manufacturing industry.

Cost of manufacturing steel-based flooring systems is reported in Klanšek and Kravanja (2006). The study includes cost of accrued materials, energy consumption, and labor, and is a relevant study because it embraces the holistic approach of measuring a wider range of resource consumption. The costing method applied in Mela and Heinisuo (2014), where feature-based cost centers are controlled by processing units, as well as the approaches described in Klanšek and Kravanja (2006) and Mela and Heinisuo (2014), combined with the TDABC method (Kaplan and Anderson 2004), have all provided valuable input to the method developed in the present work.

Objectives of the present work are to explore a parametric method for quantification of consumed resources in the manufacture of timber elements. The output of the method should serve as a quantification of competitiveness. The review has identified production time, cost, labor cost, and embodied CO_2 emissions (ECO_2) as indicators of competitiveness. The method should be parametric and have features that make it suitable as an objective function in optimization workflows. The method should be based on principles that keep the effort of implementation low.

Materials and Methods

Background and principle

The method developed and presented in this study has similarities to the aforementioned TDABC method (Kaplan and Anderson 2004). However, while TDABC uses predetermined values as inputs for activity duration, the method described here uses the parametric properties of the items being processed to calculate durations. Moreover, the outcome is not limited to costings, but also to a more detailed calculation of consumption in terms of time, overall costs, labor costs, and carbon emissions. To acknowledge its relationship with the TDABC approach, the method developed during the present study is called item-driven activity-based consumption (IDABC). Its relationship with the TDABC method and the differences between the two are explained in the following, subsequent to key definitions and programming concept.

ABC in general (Hoozée and Hansen 2014), as applied for product manufacturing, defines activities along a production line as resources that combine to perform operations in the manufacture or processing of a given item. Resources are the theoretical definition of apparatus and personnel that can contribute to an activity, whilst an activity is the physical realization of a given item. An activity is performing an operation on an item, and an item is either direct material in the manufacturing of a component, or a component in the assembly or processing of the final product (Fig. 1).

Object-oriented programming (OOP) was applied in the programming of the IDABC. OOP is generally much used in modelling of real-life applications and the concept of classes in OOP is convenient and offers excellent levels of control when a programming operation shall be repeated multiple times. Classes were defined for resources and activities, sections, bodies and assembly, and the instantiation of any of these classes generates a unique object based on a set of attributes. The object can then be treated by what is known as methods of the class to perform various programming operations of that object. OOP is not compulsory when implementing IDABC, but is mentioned to give some understanding of how the programming was performed.

The TDABC approach employs two parameters for the estimation of cost-driver rates. These are the cost per unit time of resources, and the time required to perform a given activity (Kaplan and Anderson 2004). In situations involving the costs of product manufacture, the TDABC approach would multiply cost-center rates with the duration of the relevant activities. This requires the duration of all activities to be predetermined. Any permutations from a planned manufacturing framework will impose additional planning production costs on the manufacturer during product cost determination.

The IDABC approach allows more indeterminacy, and features levels of flexibility and information content that enable the parametric accounting of manufacturing expenditures linked to the systematic and repeated manufacture of components constituting an assembly.

The initial parameter used in the IDABC method is cost of resources per unit time (C_R), where R denotes a resource. In addition to cost rate, the IDABC method also includes the rate of production of CO_2 equivalents ($CO2_R$). This is required for the completion of an environmental product declaration, which is an increasingly important factor in customer purchase motivation (Del Borghi 2013, Thies et al. 2019).

The second parameter used in the TDABC method is the predetermined duration of an activity. In the IDABC approach this is substituted by a parametric function in the activity object (the programmed representation of the activity). When an item is subject to an activity, the activity object is parsing the predefined processing Système International (SI, or metric) unit of the activity, and the item is returning the requested quantity processed by the activity. In the activity object a series of methods serves to compute an expenditure vector associated with the processing of the item. For example, during the lifting of a given item, the weight of the item in kilograms is requested. During a sawing process, depending on which saw activity that is used, either the number of items being cut (items), or the cutting area (m^2), is requested.

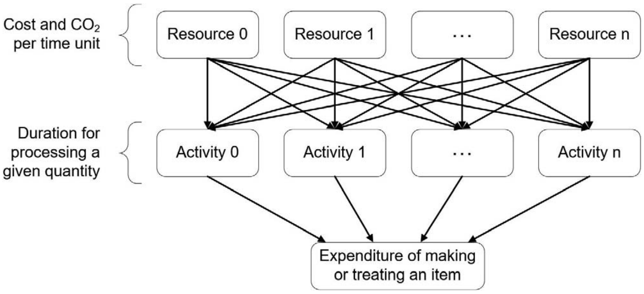

Figure 1. — Activity-based accounting in general. The relationship between resources, activity, and expenditures.

The expenditure vector $\mathbf{V}_\eta$ (Eq. 1) contains the duration of an activity (T_η, [s]), overall costs (C_η [€]), labor costs (LC_η [€]), and the amount of CO_2 equivalents (GWP_η [kg CO_2 eq]) associated with the item. The subscript η denotes a specific item subject to a given activity. Overall costs represent the total costs linked to the activity, while labor costs constitute that part of the costs associated with labor.

$$\mathbf{V}_\eta = [\, T_\eta \quad C_\eta \quad \mathrm{LC}_\eta \quad \mathrm{GWP}_\eta \,] \tag{1}$$

Principally, an item inherits an expenditure vector for each activity to which it is subjected during the production process. The total expenditure linked to manufacture of the product ($\mathbf{V}_{\text{assembly}}$) is the sum of expenditures for the activities completed as the items pass along the production line and operations for building the assembly are performed (Eq. 2). $\mathbf{V}_{\text{assembly}}$ is the output of the method, and comprises the selected indicators for competitiveness.

$$\mathbf{V}_{\text{assembly}} = \sum_{i=0}^{\text{numBody}} \sum_{j=0}^{\text{numAct}} \mathbf{V}_{i,j} + \sum_{k=0}^{\text{numAsmbly}} \sum_{l=0}^{\text{numAct}} \mathbf{V}_{k,l} \tag{2}$$

Description of the process

The IDABC process is initiated by specifying the SI units associated with the activities, and the energy sources linked to the resources. This is followed by definitions of the unique sections that constitute the product. These sections are defined on the basis of the product's general specifications as illustrated in the two upper rows in Figure 2. The IDABC approach divides the manufacturing into two subprocesses. The first of these involves the manufacture of bodies (''body level''), and the second is the assembly process that produces the final product (''assembly level''). The term ''body'' is introduced here as a more general expression also covering, e.g., coating and adhesive, and will be used to address the physical components of an assembly. Initially, the term ''component'' was used because it better communicates the physical meaning, but this term will henceforth be used in reference to vector components (elements of a linear array). In a flowchart the process is divided into four subprocesses (Fig. 2):

- Input: definitions of fasteners and sections based on specifications, materials selection, accounting figures, the energy source for resources, and the SI units associated with the activities;
- Cost centers: identification of activities and associated resources in the production line;
- Body level: construction of bodies from direct materials; and
- Assembly level: assembly of bodies make the final product.

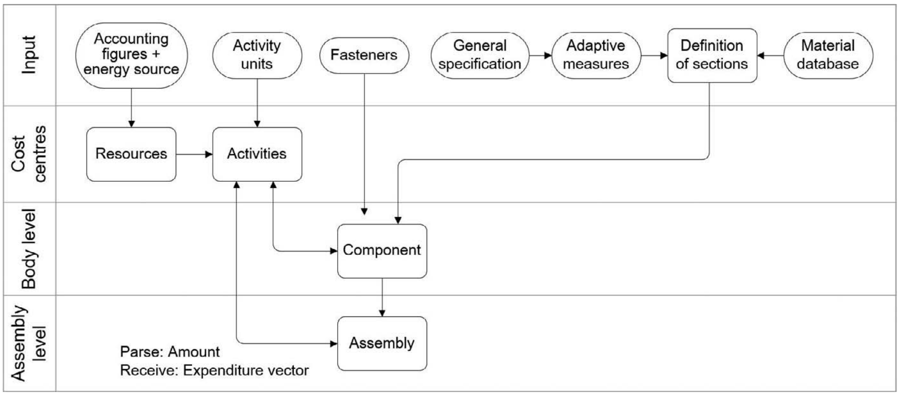

Figure 2. — Item-driven activity-based consumption method process flowchart.

Resources defined for the present study include the following:

- Operators: Human resources employed at the factory; most activities require operators.
- Joinery saw: 5D CNC machine used for linear cutting and milling operations. Direct materials used by this resource are either standard lengths or predetermined lengths from the supplier.
- Sheet-panel saw: A device used to cut structural plates. A plate is defined as a section with an aspect ratio above a given threshold.
- Overhead crane: Used for handling of items weighing above a given threshold.
- Element inverter: Equipment inverting structural plates or subassemblies through 180 degrees.
- Robotic arm: A device used to operate screwing and nailing modules.
- Glue center: In this study, only manual gluing operations are considered, and gluing is associated with operator resources. However, most technical timber product manufacturing processes employ an automatic glue center.
- Glue press: This is an optional resource by which a product is subjected to pressure during glue hardening. In this study, the resource is not included because pressure in conjunction with glue hardening is applied using screws.
- Overhead: This resource parameter encompasses costs linked to carbon emissions from the factory building, including lighting; heating, ventilation, and air conditioning (HVAC); and the use of hand tools.

In the case considered in this study, the resources used are combined to form 15 activities performed at the body level and the assembly level (Fig. 2). As is illustrated in the flowchart in Figure 3, it is possible for any given resource to contribute to a given activity, and for any given activity to contribute towards producing a given body. Furthermore, once manufactured, any given body can be incorporated into an assembly-level activity, and any assembly-level activity can contribute towards the assembly process. In Figure 3, to avoid confusion arising from an excessive number of connecting lines, only two linkage combinations (separated by continuous and dotted lines) are included for the upper three processes. The relevant resources and activities are explained in more detail in the following sections: ''Materials database'' and ''Definition of factory activities.''

Materials database

A materials database is required as an input to the method. The database contains supplier-specific information regarding the delivery format, density, unit cost (in €/m^3), and unit mass parameters for ECO_2 and uptake of CO_2 equivalents (in g/kg) for materials information modules A1–A3 (cradle-to-gate). The delivery format is structured with the primary dimension listed first, followed by the secondary dimension and, optionally, lengths.

Definition of factory resources

General form. — Factory resources are associated with two consumables: the rate of cost and the rate of CO_2 emissions. The rate of cost (C_R) is given as cost per second (€/s) and is written on general form for a given resource R in Equation 3:

$$C_R = \left(\frac{C_A}{(T_{\text{SOW}} \cdot T_{\text{OPW}} - T_{\text{UsDT}}) \cdot T_{\text{EUT}}}\right) \cdot \frac{1}{3,600} \tag{3}$$

where C_A is the annual cost of the resource as it appears in factory accounting figures, inclusive of payments on associated loans, capital consumption allowance, and the cost of scheduled maintenance and operation. T_{SOW} and T_{OPW} are the annual scheduled weeks of operation, and the scheduled hours of operation per week, respectively. T_{UsDT}

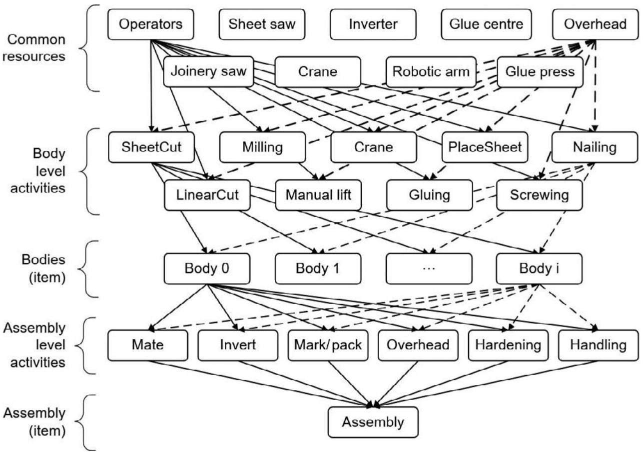

Figure 3. — Resource flow chart for the item-driven activity-based consumption method.

represents the number of hours of unscheduled downtime, and T_{EUT} is the expected uptime per time unit.

The rate of CO_2 emissions from factory operations is obtained from a combination of ECO_2 from the machinery, and emissions resulting from power consumption. Several papers, including those by Du et al. (2015) and Liu et al. (2017), address the issue of emissions from machining tools, but very little information is available on how the ECO_2 generated by any given machine is treated and distributed across the products it produces. Our approach is to calculate machinery-related ECO_2 by first distributing the effective ECO_2 from a given machine along its service time and then redistributing it to the activities that use the resource. Both the ECO_2 and the service lifetime are parameters that are specific for a given machine and the maintenance strategy of the factory, and must be entered into the method. Effective CO_2 emissions ($CO2_{\mathrm{emb,ef}}$) are calculated by subtracting the upstream ECO_2 (as installed) from the downstream ECO_2 (documented recovery as replaced or disposed) for the machinery, and then adding an estimate of the ECO_2 emitted by consumer durables, parts, and maintenance work carried out during the service lifetime of the machine. This approach provides the factory with an incentive to maintain residual service capacity in its resources, which would be the case when leasing machinery. It will also serve to reduce CO_2 emissions associated with manufacturing by encouraging late-phase maintenance and ensuring that residual CO_2 in the machinery is sustained.

The amount of CO_2 produced by a resource is a function of its energy consumption (P_R) and the energy source used in production. As is illustrated by the typical machining power profile published in Shin et al. (2017), power consumption is kept constant for the duration of the operation. This approach fails to take into consideration standby power consumption, but succeeds in taking high levels of power consumption during idle operations into account (Schudeleit et al. 2016). Emissions levels from various energy sources are defined in Schlömer et al. (2014). Median energy values from hydropower are used in the calculations performed in this study (Table 1).

The CO_2 produced by a given resource (CO_{2R}) is given by the general expression in Equation 4:

$$CO_{2^R} = \left(\frac{\frac{CO_2\mathrm{emb,ef}}{T_{\mathrm{SL}}}}{(T_{\mathrm{SOW}} \cdot T_{\mathrm{OPW}} - T_{\mathrm{UsDT}}) \cdot T_{\mathrm{EUT}}} + \frac{\frac{\mathrm{g\ CO_2eq}}{\mathrm{kWh}}\big|_{\mathrm{source}}}{1{,}000} \cdot P_R \right) \cdot \frac{1}{3{,}600} \left[\frac{\mathrm{kg\ CO_2eq}}{\mathrm{s}} \right] \tag{4}$$

Case study resources. — Table 2 lists the specific values used in the resource equations for the production line investigated in the present study. The values are defined from both empirical and probability data and are based on interviews with the production line manager. The values will change between factories depending on a variety of factors, including level of loan financing and efficiency of premises and installed inventory, salary, working hours, lean manufacture implementation levels, and maintenance strategy, to mention a few.

Table 1. — Median values for emissions derived from selected electricity supply technologies (g CO_2 eq/kWh) (Schlömer et al. 2014).

$$\frac{\mathrm{g\ CO_2eq}}{\mathrm{kWh}}\Big|_{\mathrm{source}} = \begin{bmatrix} \mathrm{Coal} & \mathrm{Gas} & \mathrm{Solar} & \mathrm{Hydro} & \mathrm{Nuclear} & \mathrm{Wind_{ocean}} & \mathrm{Wind_{land}} \\ 820 & 490 & 41 & 24 & 12 & 11 & 12 \end{bmatrix}$$

Definition of factory activities

General form. — Costs and CO_2 emissions are a function of the duration of the activity. The duration of an activity is a parametric function of processed quantity and an associated index of effort (IoE). The processed quantity is activity-specific and is defined according to how the underlying resources operate. The units associated with a processed quantity may be piece, weight (kg), length (m), area (m^2), volume (m^3), or time (s). The IoE is typically expressed in terms of machineability (feed rate), which influences the time taken to process the processed quantity. The duration of an activity (in seconds) is the first component of the expenditure vector (**V**), expressed in its general form in Equation 5:

$$\begin{aligned} \mathbf{V}_{\mathrm{component\ 1}} &= T(\mathrm{QTY}, \mathrm{IoE}) \\ &= T_{\mathrm{PRE}} + T_{\mathrm{uQTY}}(\mathrm{IoE}) \cdot \mathrm{QTY} + T_{\mathrm{CLS}} \end{aligned} \tag{5}$$

where T_{PRE} is the preparation time for the activity, T_{uQTY} is the processing rate of the activity in time per unit quantity (as a function of IoE), QTY is the processed quantity, and T_{CLS} is the time taken to close the activity. The second component of **V** is the associated overall cost (euros) of the activity, and is calculated using Equation 6, where C_{NonTD} is the non–time-dependent initial cost of the activity, n_{OP} is the number of operators, $C_{\mathrm{operators}}$ is the cost rate of the operator, and C_R is the rate of cost, as defined in Equation 3.

$$\mathbf{V}_{\mathrm{component2}} = C(T) = C_{\mathrm{NonTD}} + (C_R + n_{\mathrm{OP}} \cdot C_{\mathrm{op}}) \cdot T \tag{6}$$

The third component of **V** comprises labor costs (euros) and is calculated in Equation 7.

$$\mathbf{V}_{\mathrm{component3}} = \mathrm{LC}(T) = n_{\mathrm{OP}} \cdot C_{\mathrm{op}} \cdot T \tag{7}$$

CO_2 emissions constitute the last component of **V** and are a function of energy source (in g CO_2 eq/kWh) and resource power consumption (in kW), expressed in Equation 8.

$$\begin{aligned} \mathbf{V}_{\mathrm{component4}} &= CO_2\left(T, \frac{\mathrm{g\ CO_2eq}}{\mathrm{kWh}}\Big|_{\mathrm{source}}\right) \\ &= (CO_2R + n_{\mathrm{OP}} \cdot CO_2\mathrm{op}) \cdot T \end{aligned} \tag{8}$$

A sheet-panel saw is used as an example. The saw is operated by two persons and the unit of processing quantity is cutting area. It takes 100 seconds to prepare, and an additional 20 seconds to close the saw-cut process. A fixed non–time-dependent cost of €5 is added to the process. Depending on the density of the material, sawing takes 25, 50, or 100 s/m^2 based on a power consumption of 12 kW averaged across the time taken to complete the process. For a unit cutting area of 1 m^2 at lowest IoE, the consumption functions return the following expenditure vector: 145 s, €11.16, €2.78, 11.6e-3 kg CO_2 eq.

Case study activities. — For the product investigated in the present study the activity specifications and dependent resources are summarized in Table 3. The values are based on interviews with the production line manager and a process of calibration. The number of operators, preparation

Table 2. — Factory resource specification.

Name of factory resource	Effective ECO_2,[a,b] (kg CO_2 eq)	Service lifetime, T_{SL} (yr)	Power consumption, P_R (kw)	Annual resource cost, C_A (€/yr)	Annual scheduled operation, T_{SOW} (wk/yr)	Weekly scheduled operation, T_{OPW} (h/wk)	Expected uptime per time unit, T_{EUT} (DL)	Annual unscheduled downtime, T_{UsDT} (h/yr)
Factory operators	1,000	3	0	60,000	1,750[d]/37.5	37.5	0.85	16
Joinery saw	10,000	10	10	100,000	45	40	0.85	10
Sheet-panel saw	10,000	10	12	75,000	45	40	0.5	10
Overhead crane	10,000	20	2	5,000	45	40	0.75	10
Element inverter	1,000	15	3	5,000	45	40	0.1	10
Robotic tool arm	5,000	8	5	10,000	45	40	0.75	10
Glue center	10,000	15	3	10,000	45	40	0.5	10
Glue press	10,000	15	10	15,000	45	40	0.5	10
Overhead	50,000	25	50	75,000	45	40	1	10

[a] ECO_2 indicates embodied CO_2 emissions.

[b] Upstream (as installed) minus downstream (documented recovery as alternated) ECO_2 values for the machinery, with added estimate of the CO_2 emitted by consumer durables, parts, and maintenance work carried out during the service lifetime of the machine.

[d] Full-time equivalent for operators.

and closure times, and the non–time-dependent costs will change between factories. The values are influenced by the factory floor infrastructure, operation friendliness of depending resources, and operation strategies, to mention some factors. Furthermore, it requires documentation or understanding of the activity processes to properly define the representative processing SI unit and the processing time rate, optionally with a level of effort. Note that for the linear cut activity, the underlying resource is not influenced by machineability because the parameter T_{uQTY}(IoE) has identical values for all three components. These are adaptations based on interviews with the production line manager.

The manufactured product

A timber floor element is used as a case study to assist in describing the method. The dimensions of the element investigated are 9 m in length by 2.4 m wide. Manufacture takes up 21.6 m^2 of the production floor. Details of the floor element specifications are given in Table A1.

Sections. — A section is the two-dimensional description of a body in the assembly (see shaded area of Fig. 4). It has the following attributes:

- Cross section refers to dimensions along orthogonal axes, termed ‘‘local 2’’ and ‘‘global 3.’’ The latter coincides with the predefined assembly vertical axis e3 to give the section orientation.
- Purpose describes how the section is employed in the product. There are six predefined purposes: structural, adhesive, fastener, non-structural, insulation and technical.
- Material is associated material.
- Number is the number of times the section will be used to extrude bodies.
- Material main axis is the axis that coincides with the normal vector of the section.

Bodies. — Sections are extruded to form bodies, which are the representation of the physical members of the assembly. A body has the following attributes:

- Section is the specific section associated with the body.

Table 3. — Factory activity specification.

Factory activity	Type of operator, $C_{operators}$	No. of operators, n_{OP}	SI units of processing quantity[a]	Preparation time, T_{PRE} (s)	Time per unit quantity(function of IoE), T_{uQTY}(IoE) (s/unit)	Closure time, T_{CLS} (s)	Non–time-dependent initial cost, C_{NonTD} (€)	Resource(s), C_R
SheetPanelCut	permFactory	2	4	100	(25,50,100)	20	5	sheetPanelSaw
LinearCut	permFactory	2	1	10	(10,10,10)	10	1	joinerySaw
Milling	permFactory	2	5	100	(100,200,300)	30	10	joinerySaw
ManLift	permFactory	0	2	30	(1)	0	0	permFactory
Crane	permFactory	2	2	60	(0.1)	30	0	overheadCrane
ElementInverter	permFactory	1	1	180	(60)	60	0	elementInverter
ManGlueLine	permFactory	2	4	300	(45)	180	0	permFactory
PlaceSheet	permFactory	0	4	0	(30)	0	0	permFactory
ManScrew	permFactory	0	1	0	(60,120,240,480)	0	0	permFactory
AutScrew	permFactory	1	1	90	(5,15,30,60)	30	0	robotArm
AutNails	permFactory	1	1	90	(2)	30	0	robotArm
Mate	permFactory	1	6	0	(1)	0	0	permFactory
GluePress	permFactory	1	6	180	(1)	120	0	gluePress
MarkAndPack	permFactory	0	4	0	(45)	0	0	permFactory
Overhead	permFactory	3	4	0	(36)	0	0	overhead

[a] SI units of processing quantity: 1: piece (ea.), 2: weight (kg), 3: length (m), 4: area (m^2), 5: volume (m^3), 6: time (s).

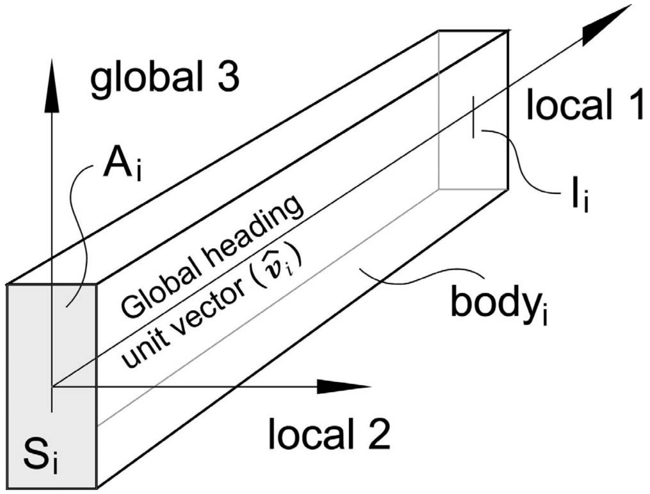

Figure 4. — Definition of section and body dimensions and orientations.

- Level is the level of the body within the assembly.
- Heading is a normal unit vector of the associated section with respect to its global axes ($\hat{\mathbf{v}}$).
- Length (l) is the extruded length of the body.
- pointOfProcess is a statement of whether body-related consumptions shall be accounted for at the factory or on site.
- index of effort is a measure of the effort invested in performing an activity, typically associated with density, machineability (feed rate), or the volume of fasteners.
- fasten spec is a specification of fasteners associated with the body.

For the floor element considered in present study (Fig. 5), bodies are grouped into levels, where the structural composites are defined as levels 1 to 3, and adhesive as level 0. Other levels built onto level 1 are numbered successively as follows: 10, 11, 12, etc. The same applies to levels 2 and 3. Figure 5 illustrates the various bodies annotated with their respective levels: a top flange (1), a core frame (2) consisting of edge joists (hatched), an edge beam (not visible) and field joists, a bottom flange (3), adhesive (0), and an internal mass (20). In the same way, additional bodies are used to describe overlays and ceiling systems. Figure 5 is viewed in the direction of the production line (e1) and with e2 and e3 also indicated.

Each body is associated with a pointOfProcess, and the activity object effectively looks up the value to decide whether activities are performed in the factory or externally.

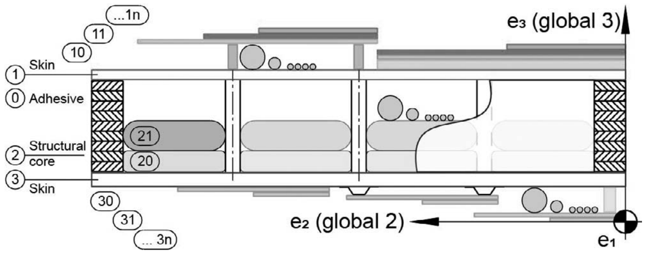

Figure 5. — Cross-section of product showing the definition of levels (viewed in the direction of the production line).

In this paper, only activities carried out in the factory are considered.

Fastener. — Fasteners are handled as an optional added feature of a body, thus activating specific activities based on the specification of the fastener. Activities related to fasteners are automatic nailing and screwing, and manual screwing. The specifications of fasteners are stored in a separate vector that is appended to bodies (see Table A2). The fastening vector consists of the following components:

1) fastener type: nail or screw;
2) diameter of the fastener;
3) direction of row of fasteners;
4) multiplier for the number of rows;
5) distance or amount: whether to calculate the number of fasteners as the distance between fasteners, or as the total number of fasteners along the number of rows
6) value of the above argument;
7) unit cost of a fastener;
8) unit (kg CO_2 eq) of a fastener; and
9) length of a fastener.

Body-level activities

The resource consumption involved in the manufacture of a body is separated in two: the amount of accrued material, and the resources invested in the activities carried out to produce the body. Consumption of material is a function of its volume and density, while input from the materials database is expressed in terms of unit costs and unit mass of CO_2 equivalents. Consumption linked to body manufacture is grouped into the body-level activities illustrated in Figure 3.

Handling and cutting. — The initial activities in body manufacture are handling and saw-cut operations. Handling is performed both before and after saw-cut activity. The handling activity depends on the weight of the body. Bodies weighing less than 25 kg are handled manually, while heavier bodies are handled using an overhead crane. Pre–saw-cut handling involves lifting direct material to the saw station for the required number of times either in standard lengths (10, 12, 13.5, or 15 m), or in the lengths delivered by the supplier. Post–saw-cut handling involves the lifting of bodies that have already been subject to cutting.

Structural bodies are cut using either a sheet-panel saw or a joinery saw. The type of saw used is determined by (1) the dimensions of the supplied material and the extent to which it conforms to body specifications, (2) the level (1 through 3) in which the body is contained, and (3) the width to height ratio of the body. A joinery saw is used unless the aspect ratio is greater than 20, in which a sheet-panel saw is used.

Milling. — Milling is performed depending on two conditions. If the thickness of the field joists is less than 36 mm, milling will be carried out on flanges in order for a slice to be created that facilitates gluing. If a fastener must be predrilled, milling will be employed to perform this operation. Predrilling will be carried out either (1) if the IoE of the body is larger than 1, or (2) if the diameter of the fastener is greater than 8 mm.

Place sheet. — For bodies with levels at between 10 and 20, or above 30, a place-sheet activity is carried out to calculate consumption related to the distribution of sheets. The activity involves both placing and cutting as a function of area.

Screwing and nailing. — The preconditions for screwing activity are factory pointOfProcess and the use of screws as fasteners as specified for a given body. If the body is at level 3 or above, or at level 1 or below, automatic screwing is used. Bodies at level 2 are fastened using manual screwing. In the case of automatic nailing, the activity is applied if the fastener is a nail and the body is at either level 10 or above, or at level 30 or below.

Gluing. — If a body is associated with level 0, either a manual or automatic gluing activity is performed for that body. In this study manual gluing is carried out as opposed to use of the automatic glue line. The activity is carried out for the area of the glue line. As it is calculated in this study, the length of the adhesive body is essentially the thickness of the glue line.

Assembly-level activities

Assembly consists of putting bodies together and incurs no material consumption other than that associated with the film used to cover the final product. Activities related to assembly include the mating of bodies, element inversion, the application of glue pressure, mark-up, packing, and final handling.

Directionality of structural bodies. — In the method developed in present study, unidirectional production can be defined as an assembly process in which the heading of all bodies is oriented in the direction of the production line. Although this is not feasible for most assemblies, a high degree of directionality in production is preferred because it reduces operational requirements and production line complexity, and reduces the time taken to position bodies. For this reason, directional production is quantified. The additional time associated with positioning bodies is not calculated in the general form (Eq. 5), but is expressed in terms of the cumulative time taken to complete body-level activities, scaled with a directionality factor. Only the volumes of structural bodies (structural volumes) are included in this measure because these are the main contributors to activities that relate to body mating and orientation. Associated additional time is used as input to an activity called ''mate'' that adds an expenditure vector to the assembly level.

The quantification of directionality begins with a calculation of the number of structural volumes that coincide with each of the production line orientations (**e**). In this study, only three orientations are used, but further orientations may be used to represent rotations or inverted elements to better reflect deviations from unidirectional production. The volumes are collected in a vector called structural volume heading (**SVH**). This is obtained by multiplying all structural volumes, $A_n \cdot l_n$, with their heading unit vector $\hat{\mathbf{v}}_\mathrm{n}$ (see Fig. 4) and summing the volumes together (Eqs. 3–9). Consequently, $\mathbf{SVH}_{\mathrm{primaryvol.}}$ contains volumes heading in the direction of the production line (primary volumes), $\mathbf{SVH}_{\mathrm{secondaryvol.}}$ has volumes perpendicular to the main direction and in-plane to the production floor (secondary volumes), and $\mathbf{SVH}_{\mathrm{tertiaryvol}}$ includes volumes normal to the production floor (tertiary volumes).

$$\mathbf{SVH} = \sum_{n=1}^{\mathrm{structBody}} \{A_n \cdot l_n\} \cdot \hat{\mathbf{v}}_n \tag{9}$$

Since small structural bodies, such as transverse stiffeners, can influence assembly friendliness even at low volumes, the **SVH** parameter is modified to reflect the number of structural bodies in the various production line orientations. This is performed by populating a vector **m,** containing the number of structural bodies in the various orientations, and a scalar **M**, which is the sum of the elements in **m**. **SVH** and **m** are then multiplied elementwise (Hadamard product) and divided by **M** to give the new, modified **nSVH**. This vector is now a representation of the directionality of volumes which also takes the number of bodies into account (Eq. 10).

$$\mathbf{nSVH} = \frac{1}{\mathbf{M}} \cdot \{\mathbf{SVH} \cdot \mathbf{m}\} \tag{10}$$

The directionality factor (DF) can now be calculated. Firstly, the ratio of primary orientation volumes represented by $\mathbf{nSVH}_{\mathrm{primaryvol.}}$ is divided by the sum of **nSVH**. If the next component of **nSVH** is greater than zero (i.e., if volumes in the secondary orientation exist), the previous term is multiplied with the ratio of secondary orientation volumes $\mathbf{nSVH}_{\mathrm{secondaryvol.}}$ by the residual sum of **nSVH**. In this paper, only three orientations are considered, so only two steps are required to calculate the DF of the assembly. However, the principle can be extended by repeating the terms of Equation 11 (below) provided there exist residual volumes in a new orientation. If all volumes of bodies are pointing in the same direction DF equals one.

$$\mathrm{DF} = \prod_{\varepsilon=1}^{|e|} \begin{cases} \dfrac{\mathbf{nSVH}[\varepsilon]}{\sum_{\psi=\varepsilon}^{|e|} \mathbf{nSVH}[\psi]} & \mathbf{nSVH}[\varepsilon] > 0 \\ 1 & \mathbf{nSVH}[\varepsilon] = 0 \end{cases} \tag{11}$$

Finally, the time of the mate activity is calculated using Equation 12:

$$\mathbf{V}_{\mathrm{mate}}[1] = \frac{\sum_{i=0}^{\mathrm{numBody}} V_i[0]}{\mathrm{DFM}} - \sum_{i=0}^{\mathrm{numBody}} \mathbf{V}_i[0] \tag{12}$$

Invert. — Invert is the second activity at the assembly level. This operation is carried out in preparation for cavity filling and top-flange mounting. It involves inverting a subassembly consisting of a bottom flange and the complete structural core after gluing and screwing have been completed. This activity is a combined operation involving both operators and machinery, and the processing unit is piece, as duration is only affected by the number of inversions.

Glue pressure. — Gluing and glue pressure may be carried out at a hardening station, involving both operators and glue press machinery. Hardening time is a predetermined quantity. Normally, glue pressure and hardening are not considered to be cost effective for production volumes of less than 250,000 m^2/yr. In the worked example involving timber floors, this activity is replaced using screws to generate glue-line pressure.

Mark-up and packing. — Mark-up and packing constitute a combined activity that employs both operators and material resources. It employs area as its processing unit, and the parsed amount is the exterior surface of the finished product. Materials consumption involves the film used to package the product.

Final handling. — Final handling of the product is carried out by operators in combination with an overhead crane and uses mass as its processing unit. The parsed amount is the transportation weight of the final product ready at the factory gates.

Overhead. — The aforementioned activities are grouped in the assembly level, where associated expenditure vectors are summarized as given in the second term of Equation 2. Production time at the factory is the sum of body time and assembly time.

The final activity is called ''overhead'' and is treated differently from other activities in that time is not associated with actual production time. Duration for this activity is a fictitious time based on the area that the assembly process occupies on the factory floor ($A_{\mathrm{resProdFlr}}$), divided by factory production capacity in area per unit time (seconds) as shown in Equation 13.

$$\mathbf{V}_{\mathrm{overhead}}[1] = \left(\frac{A_{\mathrm{resProdFlr}}}{\mathrm{capacity}_{\mathrm{areaPerSec}}}\right) \tag{13}$$

The activity overhead is derived from factory resources such as lighting, HVAC, hand tools, and the employment of three service operators. The expenditure vector uses this fictitious duration as input to calculate costs and carbon emissions.

Results

Expenditures due to an activity

Expenditures resulting from a cutting activity of the top flange is used as an example. The aspect ratio command the activity of sheet-panel cutting. This activity combines two underlying resources, and the calculation employs Equations 3 and 4, combined with data for operators and the sheet-panel saw given in Table 2. The rate of consumption of the two required resources yields the following:

$$C_{\mathrm{operators}} = \left(\frac{60{,}000}{\left(46\tfrac{2}{3}\cdot 37.5-16\right)\cdot 0.85}\right)\cdot\frac{1}{3{,}600} = 11.31\,\frac{\mathrm{c€}}{\mathrm{s}} \tag{14}$$

$$C_{\mathrm{sheetPanelSaw}} = \left(\frac{75{,}000}{(45\cdot 40-10)\cdot 0.5}\right)\cdot\frac{1}{3{,}600} = 23.28\,\frac{\mathrm{c€}}{\mathrm{s}} \tag{15}$$

$$\begin{aligned}\mathrm{CO_2operators} &= \left(\frac{\frac{1{,}000}{3}}{\left(46\tfrac{2}{3}\cdot 37.5-16\right)\cdot 0.85}+\frac{24}{1{,}000}\cdot 0\right)\\ &\quad\cdot\frac{1}{3{,}600}\\ &= 63\,\frac{\mathrm{mg\ CO_2eq}}{\mathrm{s}}\end{aligned} \tag{16}$$

$$\begin{aligned}\mathrm{CO_2sheetPanelSaw} &= \left(\frac{\frac{10{,}000}{10}}{(45\cdot 40-10)\cdot 0.5}+\frac{24}{1{,}000}\cdot 12\right)\\ &\quad\cdot\frac{1}{3{,}600}\\ &= 0.39\,\frac{\mathrm{g\ CO_2eq}}{\mathrm{s}}\end{aligned} \tag{17}$$

The rate of resource consumption calculated in the equations above enables expenditures linked to sheet-panel cutting to be calculated based on unit quantity and a duration of 1 hour. The processing SI unit (T_{uQTY}) for the sheet-panel cutting is area (m^2), and for this specific machine is 25, 50, or 100 seconds/m^2. In this example an intermediate step is taken where one unit of the processed quantity and 1 hour is inserted into Equations 5 through 8 to reveal the expenditure rates of the activity:

$$\begin{aligned}\mathbf{V}[1] &= T(1,\mathrm{IoE}) = 100+[25,50,100]\cdot 1+20\\ &= [145,170,220]\,\frac{\mathrm{s}}{\mathrm{m}^2}\end{aligned} \tag{18}$$

$$\begin{aligned}\mathbf{V}[2] &= C(3{,}600) = 5+(0.02328+2\cdot 0.01131)\cdot 3{,}600\\ &= 170.22\,\frac{€}{\mathrm{h}}\end{aligned} \tag{19}$$

$$\mathbf{V}[3] = \mathrm{LC}(3{,}600) = 2\cdot 0.01131\cdot 3{,}600 = 81.42\,\frac{€}{\mathrm{h}} \tag{20}$$

$$\begin{aligned}\mathbf{V}[4] &= \mathrm{CO_2}(3{,}600,\ 24)\\ &= (3.9\cdot 10^{-4}+2\cdot 6.3\cdot 10^{-5})\cdot 3{,}600\\ &= 1.858\,\frac{\mathrm{kg\ CO_2eq}}{\mathrm{h}}\end{aligned} \tag{21}$$

The dimensions of the top-flange body are parsed to the activity object in order to check its dimensions. The thickness of the body must conform to the top-flange thickness specification (global 3). The activity object will check if the panel requires being cut to the correct width. If cutting is required, the parsed processing unit will be defined by the thickness multiplied by the length of the top flange body. A check is then made to see if the panel requires cutting to the correct length, and the operation of cutting along a second axis is then added to the first to calculate a total cutting area.

Preparation and closure times are added only once for consecutive operations by the same activity on the same body. For this example, the cutting area is 2.4 by 0.043 m. This area is parsed to the activity object together with the density of the material. In the case of the sheet-panel saw, the IoE is controlled by density (ρ). The activity object chooses the first value in $T_{\mathrm{uQTY}}(\mathrm{IoE})$ if $\rho \le 500$ kg/m^3, the second if 500 kg/m^3 $< \rho \le 650$ kg/m^3, and the third value if $\rho > 650$ kg/m^3. The panel used in this example has a density of 510 kg/m^3 and the middle IoE value is used. Inserting parsed values into Equations 5 through 8 produces expenditure quantities rather than rates, and inserting these in Equation 14 produces the activity expenditure vector for top-flange cutting:

$$\begin{aligned}&\mathbf{V}_{\mathrm{sheetPanelSaw}}\\ &\quad = [\,125.16\ \mathrm{s}\quad €10.74\quad €2.83\quad 0.0646\mathrm{kgCO_2eq}]\end{aligned} \tag{22}$$

Case study expenditures

The complete resource consumption figures for the finalized product are presented in Table 4. The first column is the name of the cost center followed by columns of expenditures per manufactured area of the finalized timber element. The cost columns are split in total cost, and labor cost. The sums of costs related to activities (sheetPanelSaw

Table 4. — Resource consumption per area of finalized product.

Cost center	Time ($V_{\text{component 1}}$; s)	Cost (€) Total ($V_{\text{component 2}}$)	Cost (€) Labor ($V_{\text{component 3}}$)	CO_2 ($V_{\text{component 4}}$; kg CO_2 eq)
sheetPanelSaw	11.7	1.00	0.26	6.0e-3
linearSaw	6.6	0.59	0.15	2.5e-3
CNCmachine	0.0	0.00	0.00	0.0
manLift	5.8	0.07	0.07	0.4e-3
crane	96.8	2.29	2.19	23.5e-3
elementInverter	13.9	0.26	0.16	2.6e-3
manScrew	166.7	1.88	1.88	10.5e-3
autScrew	80.6	1.08	0.91	18.2e-3
autNails	0.0	0.00	0.00	0.0
manGlueLine	109.9	3.73	3.73	20.7e-3
mate	7.9	0.18	0.18	1.0e-3
gluePress	0.0	0.00	0.00	0.0
markAndPack	114.2	1.29	1.29	7.2e-3
overhead	36.0	1.64	1.22	29.9e-3
placeSheet	0.0	0.00	0.00	0.0
structural	0.0	107.75	0.00	14.331
adhesive	0.0	0.69	0.00	0.233
fasteners	0.0	1.56	0.00	1.363
nonStructural	0.0	10.94	0.00	0.300
insulation	0.0	0.00	0.00	0.0
technical	0.0	0.00	0.00	0.0
packing	0.0	0.25	0.00	0.025
Production	649.9	14.01	12.04	0.122
Material	0.0	121.19	0.00	16.252
Sum	649.9	135.20	12.04	16.375

to placeSheet), and materials (structural to packing materials) are presented in italics. The bottom row of the table shows the overall costs of the product (in bold font). Note that no materials are associated with insulation nor technical installations (e.g. piping and cables).

The production time is only associated with activities and not with accrued materials. Crane operations are time consuming, as is manual work such as gluing and final marking and packing, all typically contributing 15 percent of the production time. The screwing operations contribute 40 percent of the production time, and in particular the manual screwing operations (25%). The resulting production time for the timber element is close to 11 min/m^2.

The carbon emissions associated with manufacturing activities are very low (less than 1%), and carbon emissions are mainly stored in materials entering the factory.

To increase the readability of the cost figures in the table, the numbers are translated into two charts.

Figure 6 shows the cost distribution for the machinery and labor involved in production line activities. Figure 7 shows the overall costs of the product, distributed according to production activities (equal to the sum of activities costs in Fig. 6) and costs involved in material purpose.

As can be seen in Figure 6, the cost drivers of the manufacturing are the labor-intensive activities, contributing with 86% of the manufacturing cost. The directionality factor associated with the mating activity of bodies of the assembly, contribute 1.5 percent of the overall manufacturing cost. In perspective, the manufacturing cost only contributes 10 percent of the overall product cost as seen in Figure 7; the structural material volumes are the main cost driver overall.

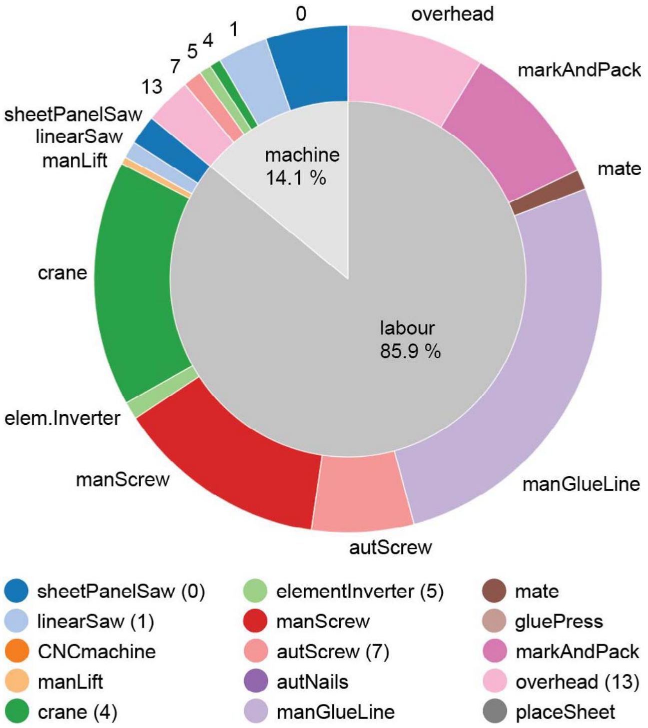

Figure 6. — Distribution of production line costs (machinery and labor).

Discussion

Principal findings

Manufacturers of timber floor elements are endeavoring to gain a market share in terms of their use in commercial buildings. Currently, a concrete hollow-core element is close to half the cost of a comparable timber floor elements

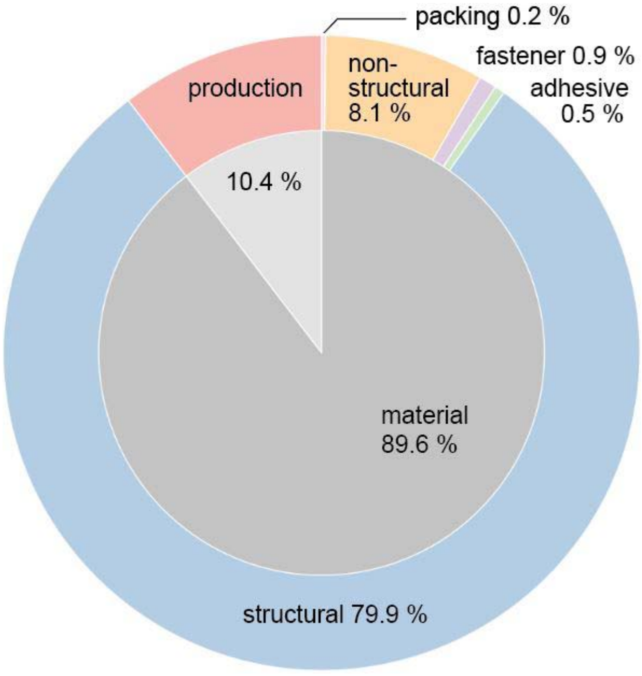

Figure 7. — Overall product costs based on production activities and materials costs.

(Norconsult Informasjonssystemer AS and Bygganalyse AS 2019). For timber floor elements this requires cost reduction to be pursued throughout the product details and in the stages of manufacturing. An optimization approach to this necessitates a parametric link between the specification of a product and the manufacturing expenditures. An accurate accounting of the cost of manufacturing is required to formulate methods of optimization of timber elements (Hu et al. 2006), and the environmental challenges the construction sector faces, emphasizing the importance of the topic. A solution to this has not been brought forward, and the present work has addressed this. The present work has developed an approach that complies with the objectives of the study. The method has certain strengths and weaknesses:

The parametric feature and the architecture of the method enable it to be implemented as a module in optimization workflows where it can be treated as an objective function for competitiveness. The method is organized to benefit from repetition of resources and activities, sections, bodies, and assembly.

Accounting of manufacturing resources requires initial steps to feed information into the model. The objective of the present work has been to seek to reduce these initial steps by exploiting the possibilities of using information stored in the items being processed, resulting in the item-driven principle. The minimum information for defining a resource is the rate of cost as taken from the accounting figures and the power consumption, whilst the optional input includes the embedded carbon emissions and the estimated service lifetime of the resource. The mandatory information for defining an activity includes the SI units of the processing quantity and the time for processing one unit of the quantity. The optional input which will enhance the precision of the accounting, includes the number and type of operators, differentiation of processing time due to an index of effort, and preparation and closure times, in addition to fixed costs of the activity. Due to this principle, a minimum amount of initial information will make the accounting run. The effort of the initial steps depend on the complexity of the production line.

Representation of minor tasks and judging which resources and activities that should be incorporated directly, and which should not, can influence both the effort of implementation and the accuracy of the method. The optional input of an activity object may contribute to the representation of minor tasks that are elsewise cumbersome to deal with.

The principle of letting an item inherit an expenditure vector is comparable to having a repository added to the item where information can be added and stored. This principle has been suitable for accumulating consumed resources, and elegantly supported by object-oriented programming. The programming principle represents a potential for further development, e.g., price and wage developments.

A factory-specific materials database must be built where information about suppliers, delivery formats, densities, cost, and embodied carbon emissions is organized. In the present work the materials database has been constructed in the form of dictionaries, which enable a product's materials provision to be associated with a choice of suppliers. The effect of selecting between different suppliers can in this way be observed directly in product resource consumption, and this feature may serve as an aid to competitiveness by revealing purchase motivation during negotiations with suppliers.

A consistent method of quantifying directionality of production volumes may suffice in expressing added production time due to positioning and alignment of items. The present work has suggested an approach in which a complex arrangement of volumes is replaced by a single directionality factor using a comprehensible term. To the authors' knowledge, no other method currently exists that reflects directionality along production lines.

Implications

An accurate parametric link between specification of a timber element and the manufacturing expenditures opens several possibilities. It formalizes and documents the accounting of resource consumption along the production line, and may facilitate the following:

- systematic calibration of the manufacture expenditures,
- investigations of excessive production-related resource consumption,
- support in relation to lean manufacturing or other resource optimizing strategies, and
- increased precision in estimated product expenditure even if the product differs from previously manufactured products.

The bottom line is the opportunity to reduce the required margins between actual expenditures and estimates offered in tenders.

Future research

The flexibility and the parametrization incorporated in the method enables a range of future studies to be performed, and a few proposals are mentioned:

- The method can be implemented in an optimization workflow, where a set of design variables (e.g., dimensions or material type) is altered by a solver to minimize an objective (e.g., cost or carbon emissions), whilst constraining serviceability performances and boundary conditions.
- Sensitivity analyses can determine how product competitiveness is responding to price developments of materials and salaries.
- The principle of separating activities in levels of completion is a useful feature and increases control of the accounting. In the present work a separation into body level and assembly level is performed, but this may be extended. Furthermore, the pointOfProcess associated with a body also enables the method to separate between location of activities. This feature can be used to extend the accounting from the factory gate to as-built. It may include transportation, installation, and completion, where resources and activities and pointOfProcess are defined accordingly.
- An interface to computer-aided manufacturing, where geometry and material definitions can be retrieved, will ease implementation.

Conclusion

An item-driven method called IDABC is developed in the present work. In compliance with the objective the method enables a parametric link to be generated between the specifications of a timber element and the quantification of manufacturing expenditures. Also, in compliance with the objective, the output of the method serves to quantify competitiveness in terms of production time, total cost, labor cost, and carbon emissions.

The parametric architecture of the method enables the implementation in an optimization workflow for timber elements. This has been the main motivation and the paramount objective of the present work, and is a response to missing efforts in the research and the ongoing endeavor of improving timber elements.

Attention to means of reducing implementation effort, as addressed in the objective, led to the item-driven approach that uses information stored in the items being processed.

As a worked example, the present study is using a timber floor element. However, irrespective of materials and production line operations, the method can be applied to generic products that involve the systematic repetition of body manufacture leading to a final assembly process. As such, the IDABC method offers indeterminacy and flexibility in production line accounting.

Definition of resources and activities in the present work was performed following interviews with a production line manager who has a thorough understanding of the operations that take place on the production line. The method has been applied to a specific timber component and assembly line operated by a major manufacturer in Norway and demonstrates good agreement with empirical data.

Acknowledgments

This work is part of a 4-year project called ''WoodSol'' (wood frame solutions for free space design in urban buildings), funded by a grant (254699/E50) from the Research Council of Norway, whose support is gratefully acknowledged. The authors would also like to express their thanks for the contributions made by fellow doctoral students Aivars Vilguts and Simone Conta during the preparation and execution of this work. We also extend our acknowledgement and gratitude to Åge Holmestad at the company Moelven Limtre AS for valuable discussions during calibration of the method.

Literature Cited

Akintoye, A. 2000. Analysis of factors influencing project cost estimating practice. *Constr. Manag. Econ.* 18(1):77–89.

Andersch, A., U. Buehlmann, J. Palmer, J. Wiedenbeck, and S. Lawser. 2013. Product costing program for wood component manufacturers. *Forest Prod. J.* 63(7/8):247–256.

Andersch, A., U. Buehlmann, J. Palmer, J. K. Wiedenbeck, and S. Lawser. 2014. Product costing guide for wood dimension and component manufacturers. General Technical Report NRS-140. US Department of Agriculture, US Forest Service. Newtown Square, Pennsylvania. 31 pp.

Cai, W., F. Liu, O. Dinolov, J. Xie, P. Liu, and J. Tuo. 2018. Energy benchmarking rules in machining systems. *Energy* 142:258–263.

Del Borghi, A. 2013. LCA and communication: environmental product declaration. *Int. J. Life Cycle Assess.* 18:293–295.

de Souza Zanuto, R., A. Hassui, F. Lima, and D. A. Dornfeld. 2019. Environmental impacts-based milling process planning using a life cycle assessment tool. *J. Clean. Prod.* 206:349–355.

Dixon, T., J. Connaughton, and S. Green. 2018. Sustainable Futures in the Built Environment to 2050: A Foresight Approach to Construction and Development. John Wiley & Sons, Oxford, UK.

Drury, C. 1992. Activity-based costing. *In:* Management and Cost Accounting. Springer, Boston, Massachussetts. pp. 273–288.

Du, Y., Q. Yi, C. Li, and L. Liao. 2015. Life cycle oriented low-carbon operation models of machinery manufacturing industry. *J. Clean. Prod.* 91:145–157.

Durga Prasad, K. G., K. Venkata Subbaiah, and K. Narayana Rao. 2014. Multi-objective optimization approach for cost management during product design at the conceptual phase. *J. Ind. Eng. Int.* 10(1):48.

Hertwich, E. G., S. Ali, L. Ciacci, T. Fishman, N. Heeren, E. Masanet, F. N. Asghari, E. Olivetti, S. Pauliuk, and Q. Tu. 2019. Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. *Environ. Res. Lett.* 14(4):043004.

Hill, C. A. S. and J. Dibdiakova. 2016. The environmental impact of wood compared to other building materials. *Int. Wood Prod. J.* 7(4):215–219.

Hoozée, S. and S. C. Hansen. 2014. A comparison of activity-based costing and time-driven activity-based costing. *J. Manag. Account. Res.* 30(1):143–167.

Howard, A. F. 1988. Modeling sawmill production, costs, and profitability as a guide to preparing bids for timber. *Forest Prod. J.* 38(3):29–34.

Hu, L., R. Tang, Y. Liu, Y. Cao, and A. Tiwari. 2018. Optimising the machining time, deviation and energy consumption through a multi-objective feature sequencing approach. *Energy Convers. Manag.* 160:126–140.

Hu, L. J., R. Desjardins, and E. Jones. 2006. Systems approach for optimizing wood-based floor construction. *In:* 9th World Conference on Timber Engineering 2006, August 6–10, 2006, Portland, Oregon; Oregon State University Conference Services. pp. 2069–2076.

Kalaiarasi, K. and E. Rajarathnam. 2015. Optimization of multi objective fuzzy integrated inventory model with demand dependent unit cost and lead time constraints. *Int. J. Appl. Eng. Res.* 10(2):4707–4721.

Kaplan, R. S. and S. R. Anderson. 2004. Time-driven activity-based costing. *Harv. Bus. Rev.* 82(11):131–138.

Klanšek, U. and S. Kravanja. 2006. Cost estimation, optimization and competitiveness of different composite floor systems—Part 1: Self-manufacturing cost estimation of composite and steel structures. *J. Constr. Steel Res.* 62(5):434–448.

Liu, Z., Y. Guo, H. Cao, G. Zhao, and Z. Liu. 2017. Embodied energy in dry cutting under consumption of tool and materials. *Procedia CIRP* 61:535–540.

Mela, K. and M. Heinisuo. 2014. Weight and cost optimization of welded high strength steel beams. *Eng. Struct.* 79:354–364.

Moore, L. and R. Creese. 1990. Manufacturing cost estimation. *Cost Eng.* 32(5):17.

Namazi, M. 2016. Time driven activity based costing: Theory, applications and limitations. *Iran. J. Manag. Stud.* 9(3):457–482.

Norconsult Informasjonssystemer AS and Bygganalyse AS. 2019. Norsk prisbok: Et oppslagsverk for byggebransjen. Norconsult informasjons-systemer AS i samarbeid med AS Bygganalyse, Sandvika, Norway.

Pomponi, F. and A. Moncaster. 2016. Embodied carbon mitigation and reduction in the built environment—What does the evidence say? *J. Environ. Manag.* 181:687–700.

Ratnasingam, J., T. Ma, and M. Perkins. 1999. Productivity in wood machining processes—A question of simple economics? *Eur. J. Wood Wood Prod.* 57(1):51–56.

Röck, M., M. R. M. Saade, M. Balouktsi, F. N. Rasmussen, H. Birgisdottir, R. Frischknecht, G. Habert, T. Lützkendorf, and A. Passer. 2020. Embodied GHG emissions of buildings—The hidden challenge for effective climate change mitigation. *Appl. Energy* 258:114107.

Schlömer, S., T. Bruckner, L. Fulton, E. Hertwich, A. McKinnon, D. Perczyk, J. Roy, R. Schaeffer, R. Sims, and P. Smith. 2014. Annex III: Technology-specific cost and performance parameters. *In:* Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York. pp. 1329–1356.

Schudeleit, T., S. Züst, L. Weiss, and K. Wegener. 2016. The total energy efficiency index for machine tools. *Energy* 102:682–693.

Shin, S.-J., J. Woo, and S. Rachuri. 2017. Energy efficiency of milling machining: Component modeling and online optimization of cutting parameters. *J. Clean. Prod.* 161:12–29.

Thies, C., K. Kieckhäfer, T. S. Spengler, and M. S. Sodhi. 2019. Operations research for sustainability assessment of products: A review. *Eur. J. Oper. Res.* 274(1):1–21.

UN Environment and International Energy Agency (IEA). 2017. Towards a zero-emission, efficient, and resilient buildings and construction sector. Global Status Report 2017. IEA.

Velarde, G., A. Pirraglia, H. Van Dyk, and D. Saloni. 2011. Lean manufacturing in the US South Atlantic Region: An overview of the current state of implementation in the secondary wood industry. *Int. Wood Prod. J.* 2(1):30–37.

Yongqian, Z., C. Meng, Y. Xuebo, and Z. Jin. 2010. A manufacturing cost estimation method based on activity-based costing. *In:* 2010 International Conference on Mechanic Automation and Control Engineering, June 26–28, 2010, Wuhan, Chia; IEEE. DOI:10.1109/MACE.2010.5536842

Appendix. Floor element specifications

Table A1. — Specification of the bodies making up the assembly.

	Height (m)	Width (m)	Length (m)	Material	Appliance	Mass (kg)	Volume (m^3)	Cost (€)	CO_2 (kg CO_2 eq)
topFlg	0.043	2.400	9.000	Kerto_Q	structural	473.7	0.929	743.04	90.00
edgJst0	0.405	0.140	9.000	GL30c	structural	219.4	0.510	306.18	23.92
edgJst1	0.405	0.140	9.000	GL30c	structural	219.4	0.510	306.18	23.92
edgBeam0	0.405	0.140	2.120	GL30c	structural	51.7	0.120	72.12	5.63
edgBeam1	0.405	0.140	2.120	GL30c	structural	51.7	0.120	72.12	5.63
fldJst0	0.405	0.066	8.720	GL28c	structural	100.2	0.233	139.85	10.93
fldJst1	0.405	0.066	8.720	GL28c	structural	100.2	0.233	139.85	10.93
fldJst2	0.405	0.066	8.720	GL28c	structural	100.2	0.233	139.85	10.93
btmFlg0	0.061	2.400	9.000	Kerto_Q	structural	672.0	1.318	1054.08	127.68
adhesive	1	10.068	0.001	Phenol-resorc.	adhesive	5.034	5.033e-3	17.62	5.03
internalMass0	0.094	0.480	8.720	Gravel 8/16	nonStructural	539.4	0.394	59.06	1.62
internalMass1	0.094	0.480	8.720	Gravel 8/16	nonStructural	539.4	0.394	59.06	1.62
internalMass2	0.094	0.480	8.720	Gravel 8/16	nonStructural	539.4	0.394	59.06	1.62
internalMass3	0.094	0.480	8.720	Gravel 8/16	nonStructural	539.4	0.394	59.06	1.62

Table A2. — The fastening vector appended to selected bodies.

	Diameter (m)	Length (m)	No.	Mass (kg)	Volume (m^3)	Cost (€)	CO_2 (kg CO_2 eq)	Type of fastener
topFlg	0.005	0.1	150	2.30	295e-6	15.00	8.61	Partial thread flange head
edgBeam0	0.008	0.28	12	1.32	169e-6	1.20	4.94	Double-threaded
edgBeam1	0.008	0.28	12	1.32	169e-6	1.20	4.94	
fldJst0	0.008	0.132	4	0.21	27e-6	0.40	0.78	
fldJst1	0.008	0.132	4	0.21	27e-6	0.40	0.78	
fldJst2	0.008	0.132	4	0.21	27e-6	0.40	0.78	
btmFlg0	0.005	0.1	150	2.30	295e-6	15.00	8.61	Partial thread flange head