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MODULAR DESIGN & CONSTRUCTION IN AUTOMOTIVE AND BUILDING STRUCTURES: ELIMINATING ‘SHOW-STOPPERS’ IN THE USE OF WOOD-BASED FAÇADE CLADDING

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Key words: products modularisation, automotive industry, building & construction, residential and commercial building, façade cladding, wood products, paints, clear coatings, paint durability, wood durability.

Abstract: The key demands on manufacturers in the modern-age markets globalisation are: (i) short development cycle, (ii) cost effectiveness, (iii) excellent product quality, and (iv) in-built product variability and upgradability. Development of new products under such dynamic market conditions necessitates an integrated approach to all stages of company operations, including product design, prototyping, productionising and manufacturing and extending it to the lifetime serviceability. Such competitive requirements cannot be dealt with by conventional, sequential model of product development and require switching to the modular approach, which additionally enables effective accommodation of growing needs of customers for products variety and their immediate or future customisation.

This paper addresses modular product development, including design and assembly in application to building & construction industry. The focus is on paving the path for new generation high-quality/high durability products, such as modular cladding components for low- and high-rise residential and commercial buildings with the emphasis on product sustainability and long-lasting aesthetics. It also considers: (i) identification of principal causes of diminishing market share of wood-based cladding of building facades, and (ii) highlights key aspects of development of a breakthrough technology providing high-quality, high-durability surface finish of painted exterior wood products offering a platform for reversal of decades-long decline of this important segment of the building products market.

Modułowa konstrukcja w przemyśle motoryzacyjnym i budowlanym: eliminowanie systemowych wad użytkowych w zastosowaniu do fasad na bazie materiału drewnopodobnego

Słowa kluczowe: modularyzacja produktów, przemysł motoryzacyjny, budownictwo, budownictwo mieszkaniowe i handlowe, okładziny elewacyjne, produkty z drewna, farby, powłoki przezroczyste, trwałość farby, trwałość drewna.

Streszczenie: Kluczowe wymagania stawiane producentom na współczesnych zglobalizowanych rynkach to: (i) krótki cykl rozwoju, (ii) efektywność kosztowa, (iii) doskonała jakość produktu, oraz (iv) „wbudowana” zmienialność produktu i możliwość jego rozbudowy. Rozwój nowych produktów w tak dynamicznych warunkach rynkowych wymaga zintegrowanego podejścia do wszystkich etapów działalności firmy, w tym również projektowania produktu, prototypowania, produkcji, oraz rozszerzenia ww. również na okres użytkowania. Tak wysokie wymagania nie mogą być osiągnięte przez konwencjonalny, sekwencyjny model opracowania produktu i wymagają przejścia na podejście modułowe, co dodatkowo umożliwia efektywne dostosowanie rosnących potrzeb klientów do różnorodności produktów i ich natychmiastowej lub przyszłej personalizacji.

Artykuł ten dotyczy rozwoju produktów modułowych, w tym projektowania i montażu w zastosowaniach w przemyśle samochodowym, budownictwie i przemyśle budowlanym. Nacisk kładziony jest na wytyczenie drogi dla produktów nowej generacji o wysokiej jakości/wysokiej trwałości, takich jak modułowe elementy fasad dla niskich i wysokich budynków mieszkalnych i komercyjnych z naciskiem na trwałość produktu i długotrwałą estetykę. Artykuł rozważa również: (i) identyfikację głównych przyczyn zmniejszającego się udziału rynkowego drewnopodobnych elewacji budynków oraz (ii) podkreśla kluczowe aspekty rozwoju przełomowej technologii zapewniającej wysoką jakość wykończenia powierzchni o wysokiej trwałości dla produktów z drewna, oferującej doskonałą platformę do odwrócenia trwającego od dziesięcioleci spadku udziału tego ważnego segmentu rynku wyrobów budowlanych.

Introduction

To deal with customer-driven demands for product customisation manufacturers operating in the current market globalisation need to achieve: (i) short development cycle, (ii) cost effectiveness, (iii) excellent product quality, and (iv) in-built product variability and upgradability. Development of new products under such dynamic market conditions necessitates an integrated approach to all stages of company operations, including product design, prototyping, productionising and manufacture, and extending it to the lifetime serviceability.

The company's ability of to quickly respond to, and exploit rapid changes in technologies, market trends and variable customer preferences is an essential attribute of all winners in commercial markets, who recognise the strategic value of leveraging their capabilities, knowledge re 'know-how', 'know-why', 'know-what' and 'know-who', and restructured their processes into a multi-levelled "modularisation" of all operations. The principal means for this are:

Product modularisation: achieved through subdivision of the entire system into principal system platforms and independent functional or stylistic modules enabling identification of components which are: (i) common to an entire family of products, and

(ii) those which facilitate product re-configuration and stylings. The latter are easily integrated into the final structure by mounting onto the principal system platform through interfaces facilitating rapid assembly and disassembly of the product,

Fixed asset parsimony approach: achieved by creating flexible 'modular business structures' through recognising that while focusing on core competency, the following issues become imperative: (i) strategic capabilities and resources in dynamic market conditions require 'structural flexibility' of entire business operations, (ii) rapid response to customer needs and variable market trends necessitates development of flexible intellectual assets, and (iii) companies cannot grow internally on short notice, necessitating the following →

Development of alliances and virtual R&D laboratories: achieved by interconnecting with other manufacturing and research establishments possessing complementary capabilities and various forms of intellectual property facilitating rapid creation of new products through outsourcing and utilising positive synergies instead of relying on own 'inflexible' capabilities and entering direct competition.

The overall structure of product family establishment process, as summarised by Jiao et. al in [1] is schematically illustrated in Figure 1.

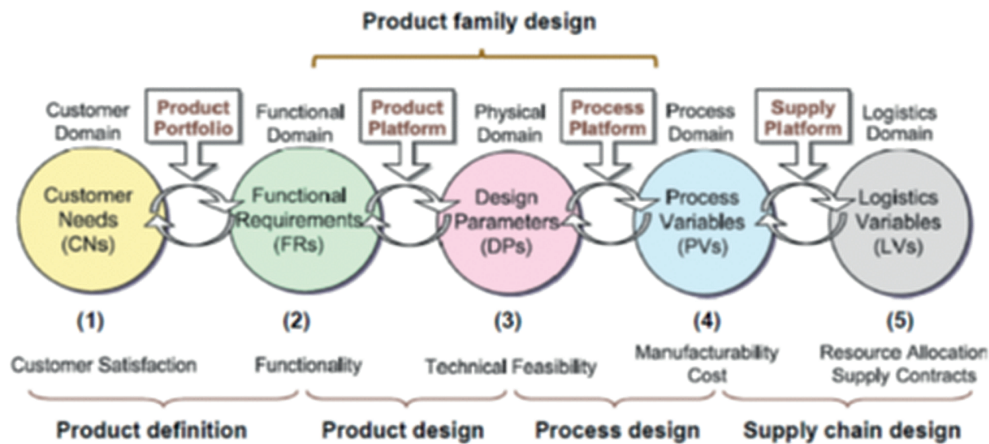


Fig. 1. Schematic structure of product family establishment over the whole spectrum of issues associated with new product development and realisation: (1) customer needs, CNs, considering also market segmentation. These are analysed by designers from the viewpoint of engineering needs and concerns from the perspective of technologies available for the product realisation; (2) Functional requirements, FRs, involving translation of these into a set of key design parameters, DPs, which must satisfy the needs of the shared product platform, (3) Establishment of design parameters, DPs, from the viewpoint of satisfying the requirements of product functionality; (4) and (5), Logistics-related domains – Process variable, PV, are established by translating DPs (Design Parameters) with the aim of generating overall production planning involving utilisation of existing company process capabilities (logistics of repetitive use of machines, tools, rigs, etc, and routing) essential for configuring production process in the manner facilitating manufacture and assembly of variable versions of products within the same product family (adopted from Jiao et.al [1])

Modular design and assembly are based on logical subdivision of products into smaller functional or decorative sub-units or building blocks which function, after their assembly, as integrated sets [3]. To achieve product functionality and upgradability, individual modules

need to be inter-connected by appropriate interfaces, whose choice depends on the functional and stylistic complexity of the system [1]. Compatibility of modules is ascertained by "design rules" governing: (1) establishing the desirable product architecture and interfaces facilitating connectivity

and ‘communication’ between modules, (2) product architecture allowing flexible assembly, decomposition, standardization and exchangeability of modules [2], and (3) standardised tests of the system to ascertain the following: (i) designated performance of each module, and (ii) appropriate interaction of modules assembled into a system. Where needed, interfaces facilitate communication between inter-connected product sub-systems [3].

Appropriately designed modular architecture subdivides the product into individual modules which can be readily re-arranged into desired configurations in the form of product variants. Individual modules in their original form, or re-styled modules can be assembled and dismantled ‘on-demand’ and replaced by new or alternative modules, thus facilitating availability of a ‘*morphing*’ real or virtual product.

Individual components (modules) can be independently manufactured in various industrial manufacturing facilities as standardised, high quality and completely finished items which are transported to an assembly plant or construction site to be rapidly assembled into a designated structure.

Due to modular structures adaptability, some product categories: cars, aircraft, ships, buildings, weapons or infrastructure elements can be easily expanded, reduced or changed by adding or removing individual modules without altering the principal platform structure, e.g. that of a vehicle or building. Such process facilitates easy change in appearance, functionality, and renovations depending on varying demands re product performance or longevity (e.g.: easy replacement of originally installed, but service-damaged or aged materials or surface finishes), or their architectural style and appeal requirements [3]. In this way new product families can be formed or extended using either: the initial, re-styled or newly developed modules without increasing the product complexity and manufacturing costs.

Overall, modularity facilitates easy generation of alternative product lines by utilising the original principal platform design which allows assembly of alternative modules exhibiting either, the originally designated or new functional and stylistic features of

the product in response to changing needs and desires of customers.

Through adoption of modularisation, the pivotal structure elements such as automotive framing systems or high-rise building’s curtain wall framing and cladding can be quickly and cost effectively designed, re-designed when needed (for instance for re-styling or refurbishing) and cost-effectively reconfigured through assembly of a variety of re-designed or newly designed/developed sub-systems onto the principal system platform.

1. Modularity in Automotive Industry

Automotive OEMs (Original Equipment Manufacturers) vigorously pursue the concept of modular design and platform sharing to minimise their development and production costs due to the fact that the platform development costs account to approximately 50% of overall costs of a new model launch.

According to Dahmus et al [4] in 2001 alone Volkswagen saved \$1.7 billion on development and production costs through developing effective product architecture and being able to share the platform and component commonality between its major brands: VW, Audi, Skoda, and Seat [5]. These included: front axles, rear axles, front ends, rear ends, exhaust systems, brake systems, and numerous other elements. Due to this Volkswagen was able to claim that all vehicles on this shared common platform are effectively differentiated in the eyes of customers.

The key structural component ascertaining structural integrity and stiffness of the vehicle is the under-body (see Figure 2) which forms the principal vehicle platform allowing integration of all vital car components, e.g. engine, transmission and suspension [5]. Any change to the shape of the under-body will affect all surrounding, interconnected components. Thus, as illustrated in Figure 2a, it limits the development of alternative designs, typically limiting production to a single vehicle variant manufactured at a dedicated assembly line due to its inherently inflexible architecture.

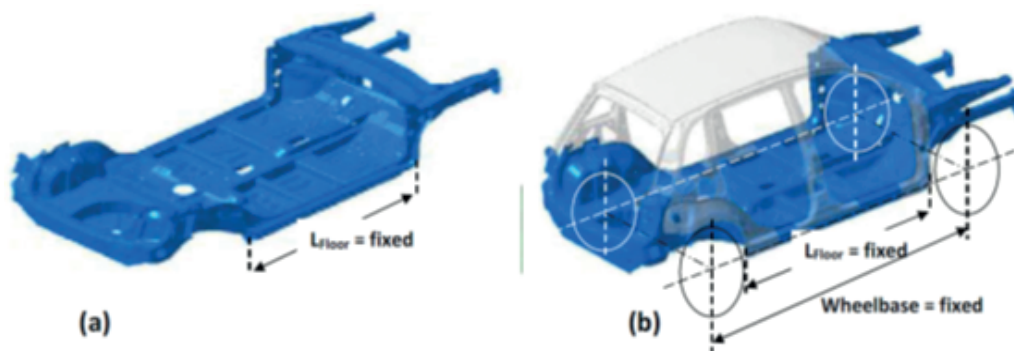


Fig. 2. a) Integral design of under-body assembly, and b) Body-in-White (BiW) with integral under-body (partially adopted from [6])

Any attempt to change the above type of platform is prohibitively costly, necessitating inefficient redesign requiring changes and additions to the existing inflexible manufacturing and assembly process.

Due to the above limitations, integral under-body systems are increasingly replaced by modular structures illustrated in Figure 3, which typically comprise the following modules: (i) The main floor (MF), (ii) Front-end module (FEM), (iii) Rear-end module (REM) and (iv) Motor (Engine) compartment (MC/EC).

The principles of modular approach to car design and assembly facilitating flexible configuration of alternative vehicle variants based on selection of appropriate modules are illustrated in Figure 3. The control of length and spatial configuration of individual modules enables fast and cost-effective customisation of vehicles in response to the market and recently, for higher-end vehicle brands, even to individual customer needs.

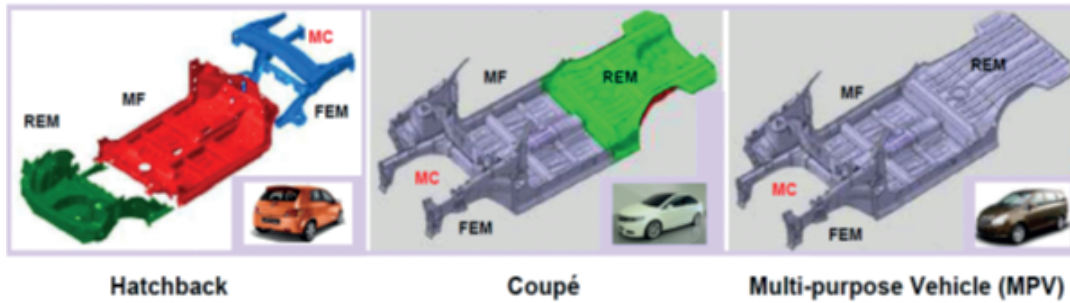


Fig. 3. Schematic illustration of car modular design regarding shared under-body platform common to a range of vehicle variants (Hatchback, Coupé, MPV) comprising flexible modules such as: (i) front-end module (FEM), (ii) motor compartment (MC), (iii) main floor (MF), (iv) rear-end module (REM). Practical examples of modular under-body platform in cars manufactured by Proton: Hatchback (Savvy), Coupé (Persona) and MPV (Exora). Note: under-body outlines adopted from [6] and [7]

The introduction of a variable main floor module facilitates the control of vehicle wheelbase, hence facilitating manufacture of diversified variants of vehicles: hatchback, coupé or multi-purpose vehicle. Additional incorporation of alternative stylised and functional

modules of the body cladding or structure enables flexible adjustment of style variety and type of functionality of assembled vehicles, as demonstrated by photos in Figure 4 presenting modular body styling solutions achieved by Nissan in its EXA 1990 vehicles range.



Fig. 4. Flexible control of spatial body architecture and functionality through modular styling approach: Nissan EXA 1990 vehicles range

2. Modularity in Design and Assembly of Building Structures and Façades

2.1 Scope of Modular Concepts in Building Construction

Modular construction is becoming increasingly popular for residential and commercial buildings of up

to four to eight storeys high. This mode of construction is carried out at two levels [8]:

1. On-site assembly of prefabricated room-sized volumetric (4-sided) units, and/or
2. On-site installation of fully finished individual panels (external cladding, partition walls, flooring panels, ceilings).

In this construction mode, fully prefabricated units and/or individual walls that are fully fitted out during in-factory

manufacture are installed on site as load-bearing ‘building blocks’, or their individual non-structural elements, such as wall panels, are installed into the building’s structural frame. The current range of applications of modular construction is in cellular-type buildings, such as hotels, student residences, defence accommodation and social housing, where the module size is compatible with manufacturing and transportation requirements.

The primary advantages of modular construction are: (i) economy of scale in manufacturing of multiple repeated units, (ii) speed of on-site installation, and (iii)

improved quality and accuracy in manufacture. Modular buildings and their integral sub-components can be potentially dismantled and reused, thereby effectively maintaining their asset value.

Figure 5 schematically illustrates the principles of modular design and construction at the level of complete multi-storey buildings with integrated individual wall panels, including definition of principal modular grids essential in modular design and construction (see an example in Fig. 5a), and 4-sided modular cells with timber cladding on wall panels (see Fig. 5b).

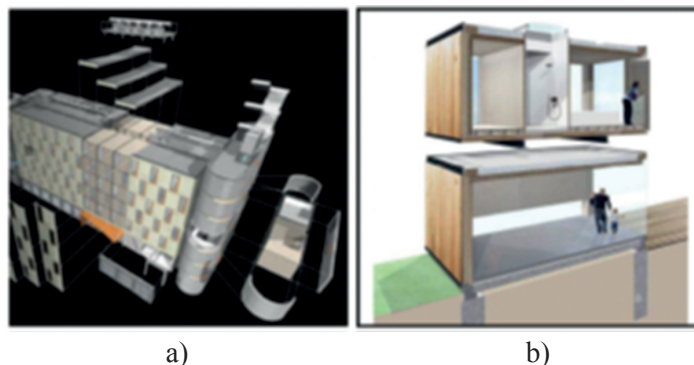


Fig. 5. Schematic illustration of modular design and construction principles: a) complete multi-storey building: adopted from [9], b) Individual modules with timber cladding on wall panels [10]

One of the largest areas of modular design and assembly in the building and construction sector are façades. Current literature in this domain has a focus on outdoor building materials such as aluminium, Alucobond® and Colorbond® to name a few. Very little has been done on timber use in architectural façades as an appearance element exhibiting insufficient longevity characteristics, i.e. suffering from poor durability on exterior exposure (excessive weathering, colour loss, etc).

The most commonly used façade systems utilise curtain walls schematically illustrated in Figure 6,

which are widely used as exterior cladding systems in medium and high-rise buildings. They comprise of light-weight, typically aluminium-based framing structures enveloping the entire building. The underlying principal modular grid is based on a lattice configuration comprising mutually interconnected vertical mullions and horizontal transoms. The curtain wall grid is filled in by modular cladding panels utilising glass, metals, composites and thin stone veneers as the main categories of currently used surface finishing architectural materials.



Fig. 6. Construction of curtain walls, architectural systems broadly utilise the principles of modular design, manufacture and on-site assembly: a) Shanghai Tower Curtain Wall (China), b) Science Research Centre, Wausau (Pennsylvania/US), c) Stick System curtain wall Reliance™ manufactured by Oldcastle [11].

As depicted in Figure 6(a) and (b), the curtain wall framing is mechanically attached to the main building structure and hence, does not transfer the floor loads, which are carried by the principal building structure. The only loads carried by curtain wall are those imposed through external wind pressure and cladding weight. These are transferred to the building structure typically at the individual floor levels.

The most commonly used cladding materials are: aluminium, glass, surface-coated metal panels

(anodised or powder-coated) and composites including green materials such as Wood-Plastic Composites (WPC), which utilise plastic matrix and cellulose fibres as reinforcing materials. These are attached to the curtain wall framing by: (i) mechanical fixing, or (ii) adhesive bonding, see Figure 7 for details) utilising structural elastomeric adhesives (high-rise building curtain walls), or high-strength self-adhesive tapes (low-level residential or commercial buildings).

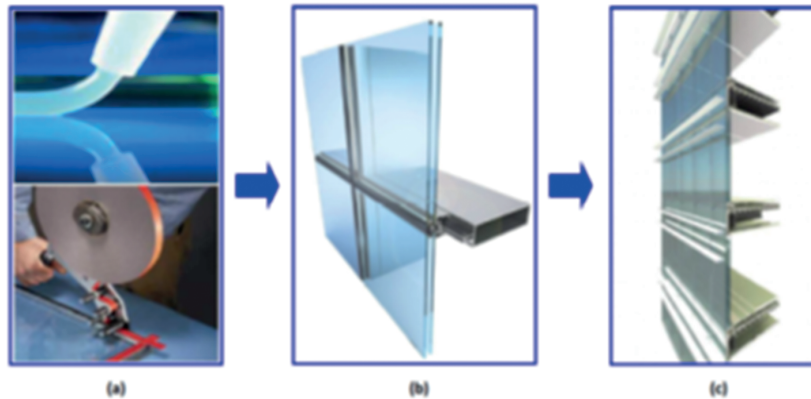


Fig. 7. Details of modular curtain wall manufacture and installation through structural glazing approach utilizing adhesive bonding of vision (glass) or solid decorative cladding panels to the framing system (mechanically attached to the building structural frame at each floor level): a) application of silicone adhesive or high-strength self-adhesive tape to the cladding panel; b) details of attachment of façade modular cladding panels to curtain wall framing by elastomeric adhesive; c) bonded cladding panels assembled in curtain wall system through aluminium framing mechanically fixed to building flooring panels [11]

2.2. Modular Approach in Timber Building Structures and Cladding

Designing and marketing exterior timber structures, including wooden façades presents inherent technical and practical challenges caused by this material's low durability and fast weathering, dimensional changes on external moisture variations, concerns with fire safety and related maintenance costs.

All of the above concerns form a platform for careful analysis of fundamental issues concerning manufacture and marketing of wood-based products family, as outlined and discussed in Figure 1 from the perspective of modularisation targeting construction of residential and commercial timber-based buildings, and in particular: wood-based cladding panels, i.e.

- 1) Customer needs (CNs) and perception regarding exterior decorative wood products, such as cladding panels, which would be able to have long-lasting (up to 20-30 years) appearance of natural, just-machined natural wood clearly showing wood texture and its natural colour. This issue needs to be analysed by designers from the viewpoint of engineering needs and concerns from the perspective of technologies available for ascertaining practical realisation of such long-lasting/low-maintenance product, and

- 2) Functional requirements (FRs) involving translation of CNs and FRs into a set of design parameters which must lead to a nearly-100% guaranteed ability of making the product satisfying the needs of the overall product platform in which wood-based façade panels will feature prominently, quickly exposing any potential deficiencies in long-term performance if and when the cladding surface would: (i) become discoloured on exposure to solar radiation, and/or (ii) suffer from undesirable peeling-off of the coating film from the wood surface (see Figure 14c demonstrating severity of these problems).

2.2.1. All-Timber High-Rise Modular Building

The design and construction of a 14-storey timber apartment building (the 'Treet' Building) in Norway provides an excellent example of effective application of a modular approach to "all-timber" building structure in the building and construction sector [12].

The building, one of the tallest timber buildings in the world consists of load-carrying glulam trusses and two intermediate strengthened floor levels. Prefabricated building modules are stacked on top of the concrete garage and on top of the strengthened levels. Cross-Laminated Timber panels (CLT), which are not a part

of the main load bearing system, are used in the elevator shaft, internal walls and balconies. The structural timber elements: supporting columns, beams and trusses are protected from rain and sun by glass and metal cladding.

Illustrations in Figures 8 and 10 below provide comprehensive details regarding practical application of

modular approach to the design and construction of this building, highlighting a step-by-step assembly process ensuring that the building can be built correctly. As seen in Figure 10, the external cladding and glazing of the building are attached to the load bearing trusses and to the balconies.



Fig. 8. a) 3-dimensional view of the completed “Treet” building: a 45-meter high building with laminated (Glulam) load-bearing structure, and b) details of Glulam-based building structure [adopted from [12]]

The assembly of the “Treet” building involved an on-site installation of prefabricated elements using a tower crane, as well as a climbing scaffolding system during the building erection. Temporary roofs are used to protect apartments, joints and timber from moisture during the building process. All main load-bearing structures in the building are wooden: Glulam is used for the columns and trusses. Cross-laminated timber (CLT)

is used for the elevator shafts, staircases and internal walls. Timber framework is used in the construction of residential modules.

All glulam elements are connected by the use of slotted-in steel plates and dowels (see details in Figure 9). This is a high capacity connection commonly used in bridges and large buildings. Typically, 8 mm steel plates and stainless steel 12 mm dowels are used [12].

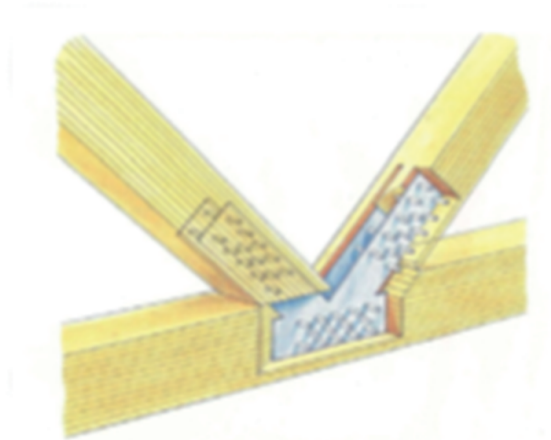


Fig. 9. Details of slotted-in steel plates connecting all structural beams and columns in the “Treet” building structure [12]

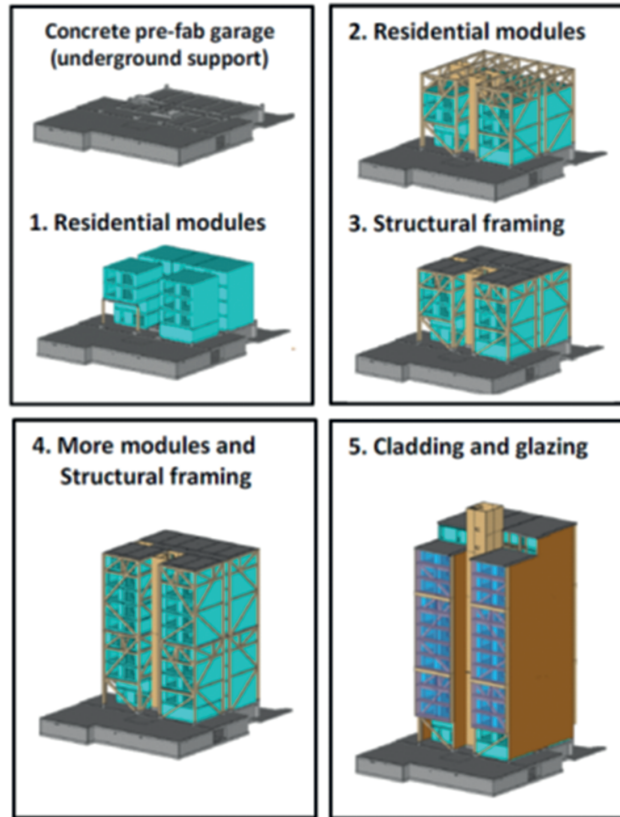


Fig. 10. Schematic visualization of the sequential (step-by-step) assembly of the “Treet” building (adopted from [12])

2.3. Addressing Critical Functional Requirements (FRs): Development of Technology Providing Durable Coatings Adhesion and Retention of Natural Wood Appearance

Issues No. 2(i) and 2(ii) outlined in Section 3.2 lead to rapid decline of market share of wood-based architectural products such as façade cladding, doors, windows and decking to their metallic or plastic equivalents regardless of the fact that these synthetic building materials do not have attributes of wood, such as attractive wood-grain aesthetics; eco-sustainability; excellent thermal insulation; fabrication ease and high strength. Regardless of all these advantageous attributes, while 20–25 years ago wooden products such as windows and doors represented 50% of the total market in Germany, USA and Australia, today’s sales are about 25% or less of the overall numbers. Such huge market share loss is due to low durability of wood against low-maintenance substitutes made of metals, plastics and wood-plastic composites (WPCs) which offer up to 20–25 years of maintenance-free service performance.

The key problems with wood products, which have inadvertently lead to the collapse of market for wood as a popular architectural façade material are: (i) rapid surface discoloration and degradation upon solar exposure, and (ii) non-performing wood coating systems

which frequently peel off from the painted surface and hence, require high-cost maintenance, i.e. 4–5 year cycles of re-painting.

The outcome of the above analysis and the assessment of current market trends lead to the formulation of key objective for the development of “winner-technology” which would facilitate the reversal of the current decline in the use of wood as an architectural finish material: it is the development of a breakthrough technology [22–26] able to ascertain elimination of paint delamination and facilitating the retention of wood’s natural appearance for up to 15–20 years when painted with clear coatings.

2.3.1. Wood as Advanced Nano-Structured Composite Material

As schematically illustrated in Figure 11, wood cells present a characteristic pattern of honeycomb-like hollow micro-tubular structures in which the strong cellulose nano-fibrils act as a high-strength reinforcing material embedded in an amorphous matrix of lignin (see Fig. 11b) performing the role of a bio-based binder responsible for the overall integrity of the wood-based substrate.

The multi-layered cell walls comprise cellulose microfibrils angularly ‘wound’ in three consecutive layers (S_1 , S_2 and S_3) distinguished from each other by different angles with respect to the cell axis (cellulose

microfibrillar angle, MFA). These tubular micro-fibrillar structures resemble those of high-strength, wound fibre hollow tubes fabricated from carbon or glass-fibre

reinforced polymeric composites. The thickest layer, S₂, constituting more than 80% of the wall, has the dominant influence on the wood mechanical properties.

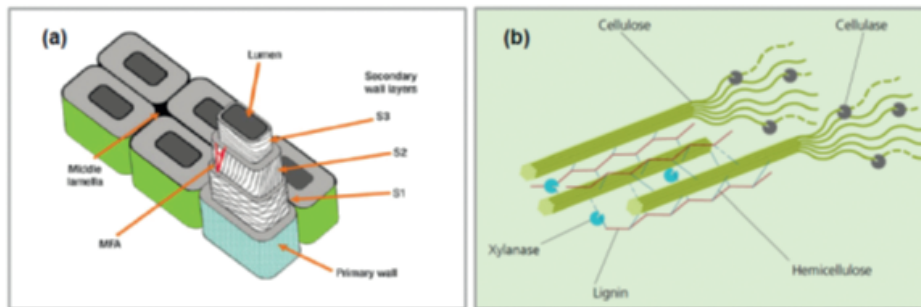


Fig. 11. a) Structure of wood fibres: S_1 , S_2 and S_3 ; the sub-layers of cellulose micro and nano-fibrils resembling the structure of high-strength wound filament hollow profiles (e.g.: pipes) fabricated from carbon or glass-fibre reinforced polymeric composites; MFA : the microfibril angle – the angle between the cellulose fibrils and the longitudinal cell axis, which is a critical factor in determining the physical and mechanical properties of wood (adapted from [13]); b) Schematic structure of wood as a biomimetic composite, presenting orientation and interactions of its key constituents in the overall structure of wood cells including cellulose microfibrils, and the role and spatial orientation of polysaccharides and lignin within wood [14].

2.3.2. The Surface Properties of Wood

Wood is a natural composite material in which strong cellulose micro- and nano-fibrils and their aggregates are embedded in an amorphous matrix of lignin performing the role of binder providing the substrate integrity (see Figure 11). Various hydrophilic and hydrophobic extractives are also present in specific tissues of trees, typically not exceeding the level of 5 % in temperate zone woods. They are unattached to the ligno-cellulosic wood matrix. Due to their relatively low molecular weight they exhibit high mobility and gradually migrate to the surface of machined wood components, thus influencing the wood hygroscopic/hydrophobic properties and durability. As schematically

illustrated in Figure 12, surface-bound extractives seriously hinder adhesion of wood. The non-polar (lipophilic) extractives such as free and esterified fatty acids and sterols form a weak boundary layer over the surface, which lowers the polarity of substrate thus reducing its wettability by polar adhesives and coatings. This phenomenon has adverse consequences demonstrated through sub-standard adhesion and long-term durability of all adhesives and surface coatings applied to the surface of timber products, particularly those made from hardwoods. Polar (hydrophilic) extractives such as tannins, other phenolic compounds and water-soluble carbohydrates contribute to long-term retention of moisture by wood surface.

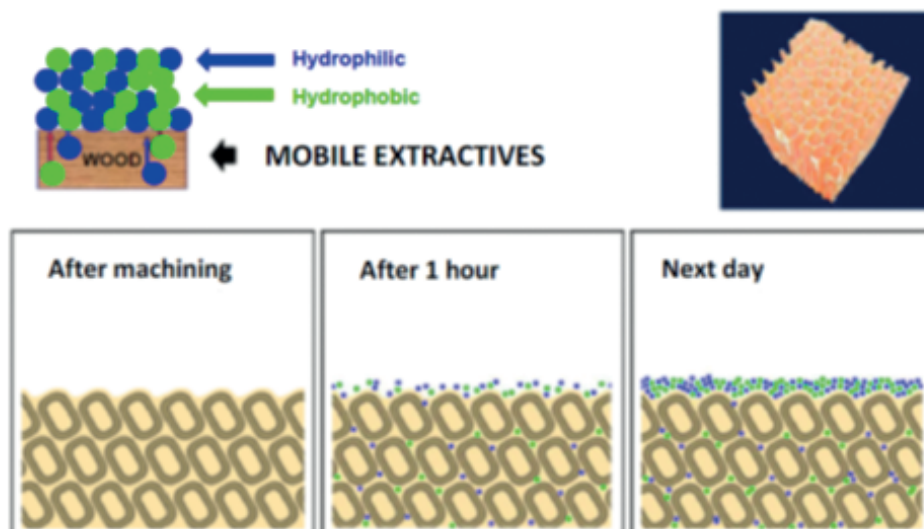


Fig. 12. Schematics of deleterious effect of wood extractives [27] progressively migrating from the bulk of a wood product to the surface (adopted from [15]).

2.3.3. Degradation of Wood Surface by UV and Moisture Exposure

An inherent poor durability of wood on exposure to UV radiation is a consequence of its chemical and morphological structure and properties of its principal polymeric constituents. Figure 13 provides schematic illustration of the uppermost surface of wood substrate subjected to solar radiation.

It is known that the UV and visible radiation penetrates the wood surface to a depth greater than $70\mu\text{m}$, resulting in significant reduction of the tensile strength (50–75% loss) to a depth of 70 to $140\mu\text{m}$. Experimental evidence shows that the strength changes may occur as far as to the depth of $280\mu\text{m}$ from the surface [16]. Discoloration of wood, demonstrated by darkening brown tint (see Figure 14a) turning into grey colour on long-term exposed wood occurs at UV radiation wavelengths range of 305–335 nm [16,18] due to the chromophoric centers in lignin (phenolic groups, double bonds, carbonyl groups, quinones, quinonemethides and biphenyls [17]) absorbing the UV light.

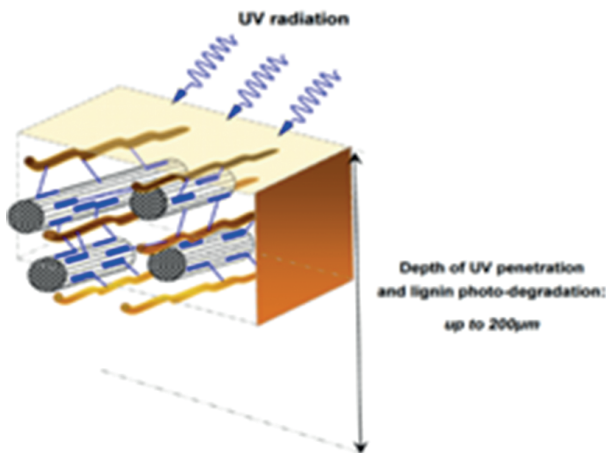


Fig. 13. Schematics of the uppermost surface of wood substrate subjected to solar radiation.

When exposed to the combination of external weather factors such as the UV- and visible light radiation, and the moisture/temperature fluctuations, the wood surface and sub-surface zone (particularly the uppermost zone, down to $85\text{--}90\mu\text{m}$ beneath the wood surface) are subjected to a variety of complex forms of photo-chemical and hydro-thermo-mechanical degradation, i.e:

1. Chain scission and subsequent loss of integrity of lignin acting as a binder within and between principal structural constituents of wood cells (cellulose nano- & micro-fibrills), and gradual discoloration of the lignin's decomposition products,
2. Cyclical water movement in wood cells.

3. Cyclical dimensional movements of the entire 3-dimensional network of wood structure, including the surface. This is stimulated by hydro-thermally controlled cyclic swelling and shrinkage due to moisture sorption/desorption cycles, and diurnal and seasonal temperature fluctuations including regular 24-hour cycles of solar heating. Swelling of wood cells upon moisture sorption additionally enhances light penetration deeper into the wood structure, hence broadening the depth of destructive effectiveness of UV and visible light.
4. Progressive surface checking and erosion leading to gradual displacement and detachment of loosened-up cellulose fibrils and splinters from the wood surface due to the combination of: (i) progressive decomposition of lignin by UV radiation, additionally assisted by the presence of oxygen, (ii) kinetic energy of rain precipitation, (iii) cyclical water movement and hydrothermal swelling-shrinking motion leading to the loss of integrity between friable fragments of wood no longer held by decomposed lignin.

As a consequence of the above mechanisms, for almost all exterior applications, the wood-based products require surface protection and surface-finishing for either: protection against the weather- and biologically-driven degradation, and for decorative and functional purposes. This is typically accomplished by the application of protective clear-coatings facilitating the retention of natural features of wood, e.g. surface colour and wood-grain appearance, or alternatively by solid colour painting, lamination with durable-species veneers, or other types of finishing materials such as decorative paper, plastic or metallic foils, stains, water-repellent materials, and others.

2.3.4. UV Degradation of Lignin: the Principal Cause of Wood Coatings Adhesion Failures

Photos in Figure 14(a) demonstrate progression of surface damage of wood panels apparent through gradually darker (brown) discoloration of their surface due to degradation of chromophoric constituents of lignin upon increased time of exposure to UV radiation [26].

Graphs in Fig. 14(b), in turn, demonstrate detrimental effects of real-time outdoor exposure of unpainted (machined only) wood, western red cedar (*Thuja Plicata*), to solar radiation before painting such pre-exposed uncoated cedar panels, on the resultant adhesion of acrylic latex (Dupont Lucide Wood Primer) and alkyd oil coating (Sherwin Williams AD-Primer); both applied after solar exposure of panels for the periods of 0 to 16 weeks.

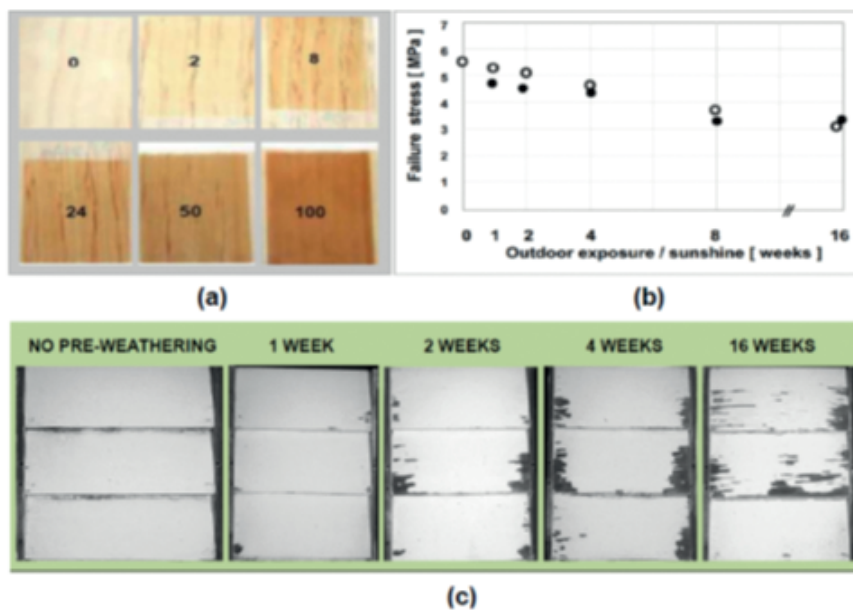


Fig. 14. (a) Progressive discoloration of *Pinus radiata* due to lignin photo-degradation on exposure (hours) to UV-B (303nm) [26]; (b) Influence of outdoor exposure to solar radiation of unpainted western red cedar on the adhesion of coatings applied after 1 to 16 weeks weathering (open circles: acrylic Dupont Lucide Wood Primer; solid circles: alkyd oil paint: Sherwin Williams AD-Primer) in comparison with unexposed surface (based on data in [19–21]), and (c) peeling-off of the poorly adhering coating film from the painted wood surface

As illustrated in Fig. 14b, it was observed [20, 21] that 4 weeks of cedar weathering prior to painting caused 25% reduction of coating adhesion which, surprisingly, was associated with 50% of specimens failing through coating delamination (paint peel-off effect). It needs highlighting that all specimens weathered for 8–16 weeks prior to painting failed by 100% coating delamination from wood. Photos in Fig. 14c illustrate the actual appearance of the same red cedar panels, showing extensive paint delamination of samples, which were exposed to UV prior to painting.

A clear conclusion from the above observations is that in order to provide effective protection of wood surface against environmental degradation by protective or decorative coatings, and in particular to alleviate the deleterious effects of degradation of lignin by the UV-driven photo-degradation, the following needs to be ascertained:

1. Coatings must be applied onto freshly machined wood which must not be exposed to solar radiation prior to painting,
2. Coatings must provide effective barrier against UV transmission through the coating,
3. Excellent coating adhesion to the underlying substrate must be ascertained.

2.3.5. Industrial Technology for Improving Adhesion to Solid Wood or Wood-Based Products

The principles of novel technology [22–25] for improving adhesion of coatings and adhesives to solid wood are schematically illustrated in Figure 15. It utilises a water-based solution of appropriate macromolecules [28] of specifically controlled length, such as polyethyleneimines (PEIs) and does not require any pre-treatment of wood before application of the primer solution.

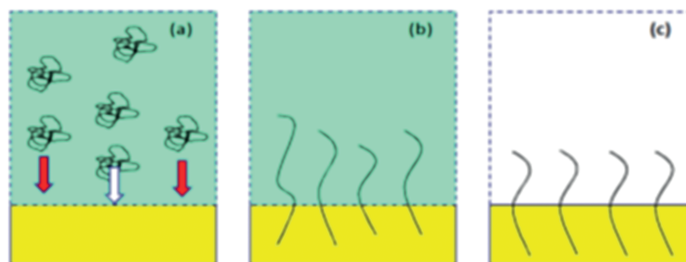


Fig. 15. Schematic principles of a novel, single-step CSIRO process for improving adhesion of coatings and adhesives to wood-based products [22–25, 28]: (a) solution of graft chemicals (PEI) in water, (b) chains of graft chemicals penetrating into the sub-surface of the treated wood-based product and chemically bonding to the wood cells; (c) treated wood surface ready for bonding.

A set of photographs in Figure 16 depicts the laboratory treatment unit for an on-line treatment of flat timber components. The photos provide good insight into the simplicity of this technology. All treated components (e.g. machined wood components) are placed on a conveyor moving at controlled speed (2–10 m/minute)

synchronized with the requirements of the manufacturing process. These are subsequently passed under the spray-head (Figure 16b) of the primer delivery system. Immediately after the spray, the treated components are flashed-off under infra-red (IR) driers and are ready for painting, bonding or any other intended use.

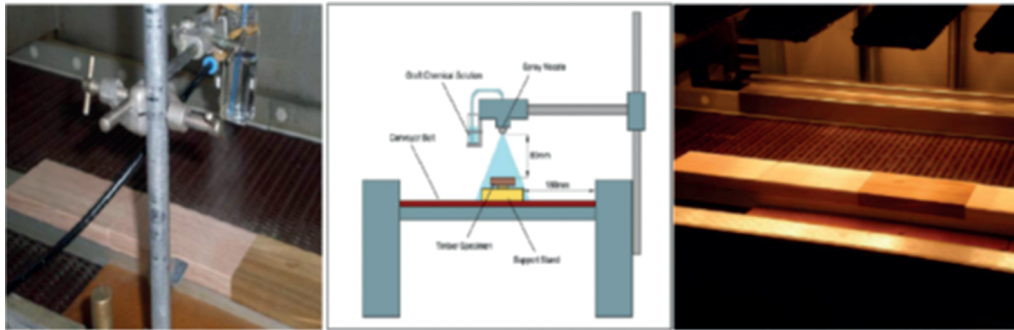


Fig. 16. Laboratory treatment unit for an on-line treatment of flat timber components for improved adhesion: (a) spray application of graft chemicals; (b) overall schematics of surface treatment, (c) Infra-red (I-R) lamps for evaporating residual water film after the spray [15].

Photos in Figure 17 illustrate the influence of alternative methods of wood surface preparation on the quality of adhesion of various high-quality architectural

coatings to the surface of European Redwood (*Pinus sylvestris*) commonly used in European window manufacturing.

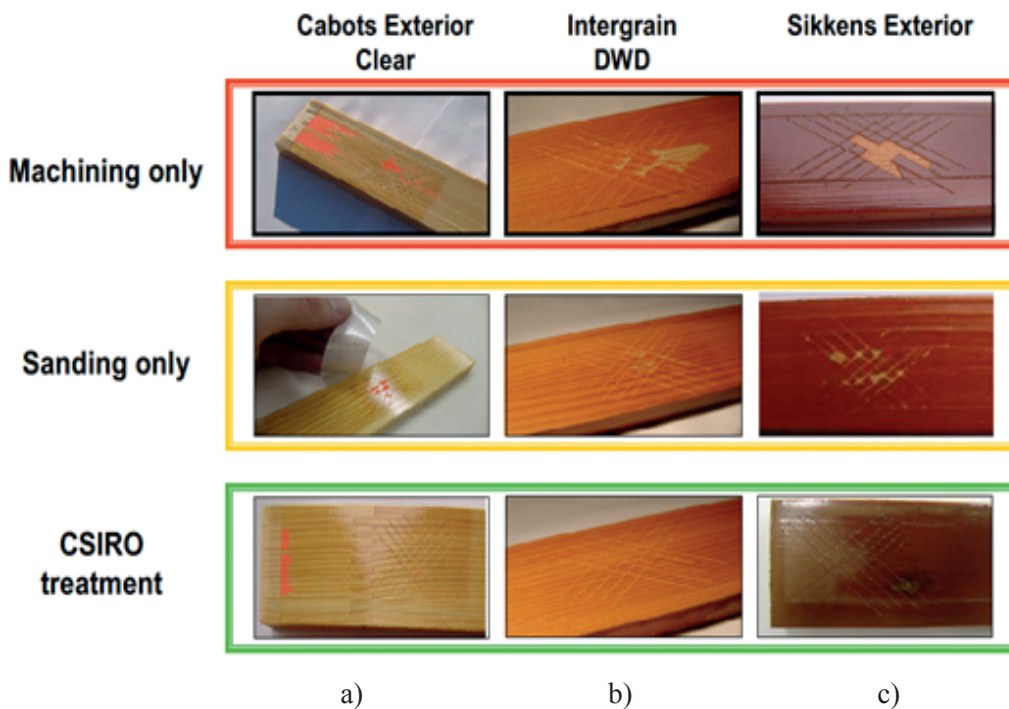


Fig. 17. Quality of adhesion of architectural coatings: Cabots Clear; Intergrain DWD; Sikkens to the surface of European Redwood (*Pinus sylvestris*): (i) machined only, (ii) machined and sanded (80 and 150 grit); (iii) molecular brush on machined surface; after 600 hours UV exposure (QUV-B; 303 nm) and 10 days immersion in 40°C water prior to paint adhesion testing (ASTM D 3359 – 95a). Data from [15].

It is clearly seen in photos presented in Figure 15 that wood surface modified by surface grafted molecular

brushes (denoted: CSIRO Treatment) completely eliminates delamination of all 3 coatings investigated in this work.

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