FIFTH EDITION

BARRY'S ADVANCED CONSTRUCTION OF BUILDINGS

STEPHEN EMMITT

WILEY Blackwell

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How to Navigate this Book

The design and construction of buildings is about making informed choices. The choices made will be specific to the context of the site, client requirements, building type and size, prevailing socio-economic conditions, and be underpinned by respect for our planet. Whatever their function, buildings need to offer a safe, healthy, stimulating and sustainable environment for all users.

The construction process will start with a thorough assessment of client needs and an equally thorough assessment of the building site, from which designs can be developed and options considered. Options will relate to where the building is to be positioned on the site, through to the general massing and appearance of the building. This is linked to significant decisions, such as whether to use loadbearing construction, framed construction, offsite or on site construction methods, or some form of hybrid approach. In turn, these decisions help direct choices about the materials to be used and the selection of elements such as walls and windows; and on to decisions about fixings, fittings, services provision and finishes.

To design buildings and to make choices about how they are to be constructed safely, economically and sustainably, requires knowledge of construction in the widest sense of the term. This encompasses knowledge about construction materials and technologies, construction techniques, economy and environmental credentials. This is underpinned by knowledge of building laws, regulations and guidance in the form of building standards and codes. The environmental impact of the choices made should underly all decisions, as these will have a long-term influence on the performance and sustainability of the building. To make effective decisions requires a long-term vision of the building, from inception and assembly, through the building's use and adaption, to disassembly and reuse of materials and components; what we refer to as a circular economy. The intention is to design and construct buildings that produce no waste and also generate more energy than they consume; an active building.

Design and construction are predicated on proposing and evaluating a variety of options for the given context. In all but the smallest of projects choices are made by a variety of professionals and tradespeople as they aim to satisfy the needs of the building sponsor, the client, within given parameters such as time, cost, quality and environmental impact. These parameters drive decisions and influence the choices made in a complex social and cultural context. The overall goal is to satisfy client requirements, while also creating a functional and delightful building that makes a positive impact on the planet. The criteria by which options are evaluated is related to the functional requirements of individual elements, components and materials; the parts that make up the whole. To do this effectively requires a thorough understanding of construction.

The original philosophy of Robin Barry – to address the functional requirements of building elements – is fundamental to making informed choices. *Barry's Introduction to Construction of Buildings* and *Barry's Advanced Construction of Buildings* are designed to inform readers about the underpinning construction principles relating to all buildings, regardless of size or intended use. This is achieved through the use of precedents, the description and illustration of 'typical solutions' to common construction challenges. In doing this, the intention is not to tell the reader how to solve the challenge before them, rather it is to provide an example that informs knowledge, and from which fundamental questions can be asked. Once we have developed an understanding of how buildings are constructed and how they may behave, we can then start to ask whether or not the techniques we use are appropriate for our context. We can apply our analytical skills to start to question conventional wisdom and to think about how we may go about doing things differently to respond to and anticipate changes in our climate and expectations of building users.

The Barry books are presented in two volumes, *Introduction* and *Advanced*, with the volumes designed to complement one another. The titles are used to reflect the stage at which these subjects are taught in colleges and universities in the UK. *Introduction* covers the first year, primarily dealing with loadbearing construction and domestic-scale developments. It also explores the common elements found in most buildings. The *Advanced* volume includes material usually taught in the second to third year, primarily dealing with offsite techniques framed construction and reuse of existing buildings. Combined, the two volumes take the reader through the entire life cycle of a building, from inception and construction to the building in use and eventual demolition, recycling and reuse of valuable resources.

An overview of the chapters in each volume is provided in Table 1, as an aid to navigation of the books.

Table 1 Overview of the chapters

Chapter	Introduction	Advanced
1	Introduction	Introduction
2	Site Analysis, Set-Up, Drainage and Scaffolding	Offsite Construction
3	Ground Stability and Foundations	Pile Foundations, Substructures and Basements
4	Floors	Single Storey Frames, Shells and Lightweight Coverings
5	Loadbearing Walls	Structural Timber Frames
6	Roofs	Structural Steel Frames
7	Windows	Structural Concrete Frames
8	Doors	Envelopes to Framed Buildings
9	Stairs and Ramps	Lifts and Escalators
10	Surface Finishes	Fit Out and Second Fix
11	Internal Environment and Energy Supply	Existing Buildings: Pathology, Upgrading and Demolition
12	Water Supply and Sanitation	

Chapters are designed so that they can be read from front to back or they can be dipped into as the need arises. Each chapter or section introduces the primary functional requirements and then the reader is introduced to an increasing level of detail. The illustrations and photographs are provided to enhance our understanding of the main principles. At a glance, sheets are used for each chapter to address the main what, why, how and when questions.

If readers are studying, for example, loadbearing construction, then they will need to read the *Introduction* volume and focus on specific chapters to supplement their learning in the classroom. In this situation, the reader will need to read chapters all the way through in the first instance, perhaps returning to specific issues, such as the position of the damp-proof course. Similarly, if readers are studying framed construction, the *Advanced* volume will be a valuable resource, supplemented with material on, for example, doors and windows from the *Introduction* volume. When it comes to revising for examinations in construction technology, the 'At a glance' feature will be useful in prompting one's memory, prior to revisiting key issues within the chapter. Chapters conclude with guidance on additional sources and reflective exercises. The reflective exercises aim to help readers question why and how we are constructing buildings in the way we do. These can be addressed by individual readers and also by small study groups as primers for discussion. We have set these in the context of (design) project work, so whatever the scale of the project or level of study the exercises should help readers to reflect on the most appropriate solution for a given context.

The principles and details illustrated here are intended as a guide to the construction of buildings. When readers use the books to help detail their building designs, dipping into chapters to see solutions to typical detailing problems will help with understanding. It is, however, important that we understand the principles underlying the construction of buildings – what needs to be achieved and why. Thus, the details and photographs provided give an indication of how it could be done; not how it should be done. Details should not be copied without thinking about what is really going on. This also applies to details given in guidance documents and manufacturers' information.

Readers should be asking questions such as: How is the building to be assembled, maintained and disassembled safely and efficiently? Is the detail in question entirely suitable for the task at hand? We make this point because building practices and regulations vary from region to region and country to country. For example, a building located in a wet and sheltered area of the UK may benefit from a pitched roof with a large overhang, but a similar building in a dry and exposed part of the country may benefit from a pitched roof with clipped eaves or even a flat roof. It is impossible to cover every eventuality for every reader in these books. Instead, we would urge readers to engage in critical thinking, analyse the details, and then seek out more sustainable approaches and products.

1 Introduction

In *Barry's Introduction to Construction of Buildings,* we provided an introductory chapter that set out some of the requirements and conditions relevant to all building projects, regardless of size and complexity. We continue the theme in this chapter, with some additional requirements. In this volume, the emphasis shifts from domestic to larger-scale buildings, primarily residential, commercial and industrial buildings constructed with loadbearing frames. This is supported by information on fit out and second fix, lifts and escalators, and offsite construction. Many of the principles and techniques set out in the introductory volume are, however, still appropriate to this volume. Similarly, many of the technologies described here are also used in smaller buildings. Thus, we would urge readers to consult both volumes of the *Barry* series. In this introductory chapter, we start to address some additional, yet related, issues, again with the aim of providing context to the chapters that follow.

1.1 The function and performance of buildings

Structure and fabric

It is the combined performance of the structure and building fabric, together with the integration of services, which determines the overall performance of the building during its life. In loadbearing construction, the materials forming the structural support also provide the fabric and hence the external and internal finishes. In framed structures, the fabric is independent of the structure, with the fabric applied to the loadbearing structural frame.

Loading
Buildings need to accommodate the loads and forces acting on them if they are to resist collapse. One of the most important considerations is how forces are transferred within the structure. Buildings are subject to three types of loading:

(1) *Dead loads*. Dead loads remain relatively constant throughout the life of a building, unless it is remodelled at a future date. These loads comprise the combined weight of the materials used to construct the building. Loads are transferred to the ground via the foundations. Because the weight of individual components is known, the dead load can be easily calculated.

Barry's Advanced Construction of Buildings, Fifth Edition. Stephen Emmitt.

(2) *Live loads*. Unlike dead loads, the live loads acting on a building will vary. Live loads comprise the weight of people using the building, the weight of furniture and equipment, etc. Seasonal changes will result in (temporary) live loading from rainfall and snow. Structural design calculations assume an average maximum live load based on the use of the building (plus a safety factor). If the building use changes, then it will be necessary to check the anticipated live loading against that used at the design stage.

(3) *Wind loads*. All buildings are subject to wind loading. Maximum wind loads (gusts) are determined by considering the maximum recorded wind speed in a particular location and adding a safety factor. Wind loading is an important consideration for both permanent and temporary structures. It is also an important consideration when designing and installing temporary weather protection to protect building workers and work in progress from the elements.

When the total loading has been calculated for the proposed building, it is then possible to design the building structure (the structural frame) and the foundations. This needs to be done in conjunction with the design of the building envelope.

Structural frames

Timber, steel and reinforced concrete are the main materials used for structural frames (Photograph 1.1). In some cases, it is common to use one material only for the structural frame (e.g. timber). In other situations, it may be beneficial to use a composite frame construction (e.g. concrete and steel). Combining two or more materials is known as hybrid construction. The benefits of one material over another need to be considered against a wide variety of design and performance parameters, such as the following:

- ❑ Extent of clear span required.
- ❑ Height of the building.
- ❑ Extent of anticipated loading.
- ❑ Fire resistance and protection.
- ❑ Embodied energy and associated environmental impact.
- ❑ Ease of fixing the fabric to the frame (constructability).
- ❑ Availability of materials and labour skills.
- ❑ Extent of prefabrication desired.
- ❑ Site access (restrictions).
- ❑ Erection programme and sequence.
- ❑ Maintenance and ease of adaptability.
- ❑ Ease of disassembly and reuse of materials.
- ❑ Life cycle costs.

Dimensional stability

Stability of the building as a whole will be determined by the independent movement of different materials and components within the structure over time – a complex interaction determined by the dimensional variation of individual components when subjected to changes in moisture content, changes in temperature and not forgetting changes in loading:

Photograph 1.1 Framed building under construction.

- *Moisture movement*. Dimensional variation will occur in porous materials as they take up or, conversely, lose moisture through evaporation. Seasonal variations in temperature will occur in temperate climates and affect many building materials. Indoor temperature variations should also be considered.
- *Thermal movement*. All building materials exhibit some amount of thermal movement because of seasonal changes in temperature and (often rapid) diurnal fluctuations. Dimensional variation is usually linear. The extent of movement will be determined by the temperature range the material is subjected to, its coefficient of expansion, its size and its colour. These factors are influenced by the material's degree of exposure, and care is required to allow for adequate expansion and contraction through the use of control joints.
- *Loading*. Dimensional variation will occur in materials that are subjected to load. Deformation under load may be permanent; however, some materials will return to their natural state when the load is removed. Thus live and wind loads need to be considered too.

Understanding the different physical properties of materials will help in detailing the junctions between materials and with the design, positioning and size of control joints. Movement in materials can be substantial and involve large forces. If materials are restrained in such a way that they cannot move, then these forces may exceed the strength of the material and result in some form of failure. Control joints, sometimes described as 'movement joints' or 'expansion joints', are an effective way of accommodating movement and associated stresses.

Designers and builders must understand the nature of the materials and products they are specifying and building with. These include the materials' scientific properties, structural properties, characteristics when subjected to fire; interaction with other materials, anticipated durability for a given situation, life cycle cost, service life, maintenance requirements, recycling potential, environmental characteristics such as embodied energy, health and safety characteristics, and, last but not least, their aesthetic properties if they are to be seen when the building is complete. With such a long list of considerations, it is essential that designers and builders work closely with manufacturers and consult independent technical reports. A thorough understanding of materials is fundamental to ensuring feasible constructability and disassembly strategies. Consideration should be given to the service life of materials and manufactured products, since any assembly is only as durable as the shortest service life of its component parts.

Tolerances

To be able to place individual parts in juxtaposition with other parts of the assembly, a certain amount of dimensional tolerance is required. Construction involves the use of labour, either remote from the site in a factory or workshop, or on site, but always in combination. Designers must consider all those who are expected to assemble the various parts physically into a whole, including those responsible for servicing and replacing parts in the future, so that workers can carry out their tasks safely and comfortably.

With traditional construction, the craftsmen would deal with tolerances as part of their craft, applying their knowledge and skill to trim, cut, fit and adjust materials on site to create the desired effect. In contrast, where materials are manufactured under carefully controlled conditions in a factory, or workshop, and brought to site for assembly, the manufacturer, designer and contractor must be confident that the component parts will fit together, since there is no scope to make adjustments to the manufactured components. Provision for variation in materials, manufacturing and positioning is achieved by specifying allowable tolerances. Too small a tolerance and it may be impossible to move components into position on site, resulting in some form of damage; too large a tolerance will necessitate a degree of 'bodging' on site to fill the gap – for practical and economic reasons, both situations must be avoided. There are three interrelated tolerances that the designer must specify, which are related specifically to the choice of material(s):

(1) *Manufacturing tolerances*. Manufacturing tolerances limit the dimensional deviation in the manufacture of components. They may be set by a standard (e.g. ISO), by a manufacturer and/or the design team. Some manufacturers are able to manufacture to tighter tolerances than those defined in the current standards. Some designers may require a greater degree of tolerance than that normally supplied, for which there may well be a cost to cover additional tooling and quality control in the factory.

(2) *Positional tolerances*. Minimum and maximum allowable tolerances are essential for convenience and safety of assembly. However, whether the tolerances are met on site will depend upon the skills of those doing the setting out, the technology employed to erect and position components, and the quality of the supervision.

(3) *Joint tolerances*. Joint tolerances will be determined by a combination of the performance requirements of the joint solution and the aesthetic requirements of the designer. Functional requirements will be determined through the materials and technologies employed. Aesthetic requirements will be determined by building traditions, architectural fashion and the designer's own idiosyncrasies.

As a general rule, the smaller (or closer) the tolerance, the greater the manufacturing costs and the greater the time for assembly and associated costs. Help in determining the most suitable degree of tolerance can be found in the technical literature provided by trade associations and manufacturers. Once the tolerances are known and understood in relation to the overall building design, it is possible to compose the drawings and details that show the building assembly. Dimensional coordination is important to ensure that the multitude of components fit together correctly, thus ensuring smooth operations on site and the avoidance of unnecessary waste through unnecessary cutting. A modular approach may be useful, although this may not necessarily accord with a more organic design approach.

Flexibility and the open building concept

The vast majority of buildings will need to be adjusted or adapted in some way to accommodate the changing needs of the building users and owners. In domestic construction, this may entail the addition of a small extension to better accommodate a growing family, conversion of unused roof space into living accommodation or the addition of a conservatory. Change of building owner often means that the kitchen or bathroom (which may be functional and in a good state of repair) will be upgraded or replaced to suit the taste and needs of the new building owners. Thus, what was perfectly functional to one building user is not to another, necessitating the need for alterations.

In commercial buildings, a change of tenant can result in major building work, as, for example, internal partition walls are moved to suit different spatial demands. Change of retailer will also result in a complete refitting of most shop interiors. These are just a few examples of the amount of alterations and adaptations made to buildings, which, if not planned and managed in a strategic manner, will result in a considerable amount of material waste. Emphasis should be on reusing and recycling materials as they are disassembled and, if possible, the flexibility of internal space use.

Although these are primarily design considerations, the manner in which materials and components are connected can have a major influence on the ease, or otherwise, of future alterations.

Flexibility and adaptability

Designing and detailing a building to be flexible and adaptable in use presents a number of challenges, some of which may be known and foreseen at the briefing stage, but many of which cannot be predicted. Thought should be given to the manner in which internal, non-loadbearing walls are constructed and their ease of disassembly and reuse (repositioning).

Similarly, the position of services and the manner in which they are fixed to the building fabric need careful thought at the design and detailing stage. For example, a flexible house design would have a structural shell with non-loadbearing internal walls (movable partitions, folding walls, etc.), zoned underfloor space heating (allowing for flexible use of space) and carefully positioned wet and electrical service runs (in a designated service zone or service wall).

Open building

The open building concept aims to provide buildings that are relatively easy to adapt to changing needs, with minimum waste of materials and little inconvenience to building users. The main concept is based on taking the entire life cycle of a building and the different service lives of the building's individual components into account. Since an assembly of components is dependent upon the service life of its shortest-living element, it may be useful to view the building as a system of time-dependent levels. Terminology varies a little, but the use of a three-level system, primary, secondary and tertiary, is common. Described in more detail, the levels are:

- *The primary system*. Service life of approximately 50–100 years. This comprises the main building elements, such as the loadbearing walls and roof or the structural frame and floors and roof. The primary system is a long-term investment and is difficult to change without considerable cost and disruption.
- *The secondary system*. Service life of approximately 15–50 years. This comprises elements such as internal walls, floor and ceiling finishes, building services installations, doors and vertical circulation systems such as lifts and escalators. The secondary system is a medium-term investment and should be capable of replacement or adaptation through disassembly and reassembly. The shorter the service life of components, the greater the need for replacement, hence the need for easy and safe access.
- *The tertiary system*. Service life of approximately 5–15 years. This comprises elements such as fittings and furniture and equipment associated with the building use (e.g. office equipment). The tertiary system is a short-term investment and elements should be capable of being changed without any major building work.

Applying this strategy to a development of, for example, apartments, the structure and external fabric would be the primary system. The secondary system would include kitchens, bathrooms and services. The tertiary system would cover items such as the furniture and household appliances. If a discrete, modular system is used, then it is relatively easy to replace the kitchen or bathroom without major disruption and to recycle the materials. This 'plug-in' approach is certainly not a new concept but has started to become a more realistic option as the sector has started to adopt offsite production (see also Chapter 2).

Security

Security of buildings and their contents (goods and people) is a primary concern for the vast majority of building sponsors and owners. In residential developments, the primary concern is with theft of property, with emphasis on the integrity of doors and windows. In commercial developments, the concern is for the safety of the people using the building and for the security of the building's contents. The desire to keep the building users and contents safe has to be balanced with the need to allow safe evacuation in the case of a fire or an emergency. Vandalism and the fear of terrorist attacks are additional security concerns, leading to changes in the way buildings are designed and constructed. Measures may be passive, active or a combination of both.

Passive security measures

A passive approach to security is based on the concept of inherent security measures, where careful consideration at the design and detailing phase can make a major difference to the security of the building and its contents. Building layout and the positioning of, for example, doors and windows to benefit from natural surveillance need to be combined with the specification of materials and components that match the necessary functional requirements. The main structural materials and the method of construction will have a significant impact on the resistance of the structure to forced entry. For example, consideration should be given to the ease with which external cladding may be removed and/or broken through, and depending on the estimated risk, an alternative form of construction may be more appropriate. Unlawful entry through roofs and rooflights is also a potential risk. Building designers must consider the security of all building elements.

Ram raiding, the act of driving a vehicle through the external fabric of the building to create an unauthorised means of access and egress for the purposes of theft, has become a significant problem for the owners of commercial and industrial premises. Concrete and steel bollards, set in robust foundations and spaced at close centres around the perimeter of the building, are one means of providing some security against ram raiding, especially where it is inappropriate to construct a secure perimeter fence.

Active security measures

Active security measures, such as alarms and monitoring devices, may be deployed in lieu of passive measures or in addition to inherent security features. For new buildings, active measures should be considered at the design stage to ensure a good match between passive and active security. Integration of cables and mounting and installation of equipment should also be considered early in the detailed design stage. Likewise, when applying active security measures to existing buildings, care should be taken to analyse and utilise any inherent features. Some of the active measures include:

- Intruder alarm systems.
- Entrance control systems in foyers/entrance lobbies.
- Coded door access.
- CCTV monitoring.
- Security personnel patrols.

Health, safety and wellbeing

Various approaches have been taken to improve the health, safety and wellbeing of everyone involved in construction. These include more stringent legislation, better education and training of workers, and better management practices. Similarly, a better understanding of the sequence of construction (a combination of constructability principles and detailed method statements) has helped to identify risk hazards and to minimise or even eliminate them. This also applies to future demolition of the building, with a detailed disassembly strategy serving a similar purpose. There are four main, interrelated stages to consider. They are:

(1) *Prior to construction*. The manner in which a building is designed and detailed, i.e. the materials selected and their intended relationship to one another, will have a significant bearing on the safety of operations during construction. Extensive guidance is available via the Safety in Design (http://www.safetyindesign.org).

(2) *During construction*. Ease of constructability will have a bearing on safety during production. Offsite manufacturing offers the potential of a safer environment, primarily because the factory setting is more stable and easier to control than the constantly changing construction site. However, the way in which work is organised and the attitude of workers towards safety will have a significant bearing on accident prevention.

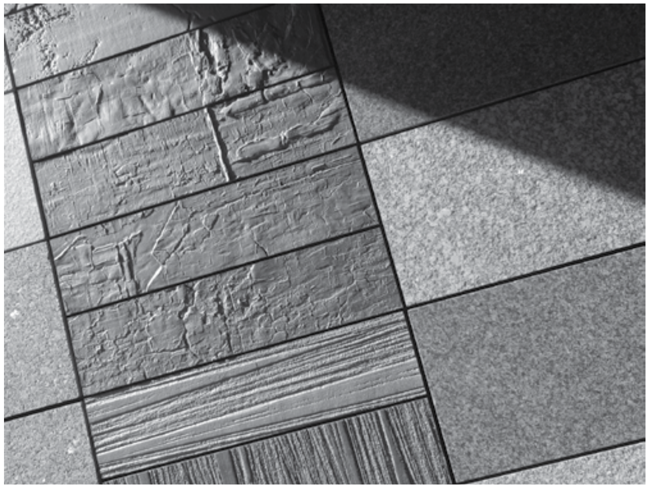
(3) *During use*. Routine maintenance and repair is carried out throughout the life of a building. Even relatively simple tasks such as changing a light bulb can become a potential hazard if the light fitting is difficult to access. Elements of the building with short service lives (and/or with high maintenance requirements) must be accessed safely.

(4) *Demolition and disassembly*. Attention must be given to the workers who at some time in the future will be charged with disassembling the building. Method statements and guidance on a suitable and safe demolition and disassembly strategy are required at the design stage.

1.2 New methods and products

An exciting feature of construction is the amount of innovation and change constantly taking place in the development of new materials, methods and products, many of which are used in conjunction with the more established technologies. Some of the more obvious areas of innovative solutions are associated with: changing regulations (e.g. airtightness requirements); changing technologies (e.g. new cladding systems); the trend towards greater use of offsite production (e.g. volumetric system build); advances in building services (e.g. provision of broadband); a move to the use (and reuse) of recycled materials (e.g. products manufactured from recycled material, see Photograph 1.2); and the drive for low- or zero-carbon construction, which has stimulated renewed interest in natural materials and their innovative use. Many of the changes are, however, quite subtle as manufacturers make gradual technical 'improvements' to their product portfolio. This could be as simple as gradually increasing the amount of recycled content in their products. Gradual innovations are often brought about by the use of a new production plant and automated production and/or are triggered by competition from other manufacturers, with manufacturers seeking to maintain and improve market share through technical innovation. In the vast majority of cases, this results in building products with improved performance standards and improved environmental credentials.

Combined with changing fashions in architectural design and manufacturers' constant push towards the development of new materials and products, we are faced with a very wide range of systems, components and products from which to choose. All contributors to the design and erection of buildings, from clients and architects to contractors and specialist subcontractors, will have their own attitude to new products. Some are keen to use new products and/or new techniques, while others are a little more cautious and tend to stick to what they know. Whatever one's approach, it is important to keep up to date with the



Photograph 1.2 Artificial stone made entirely from recycled rubber tyres (left of picture, rough texture) adjacent to natural stone (right of picture, smooth texture).

latest product developments and to investigate those products and methods that may well prove to be beneficial. Maintaining relationships with product manufacturers is one way of achieving this; indeed, we would urge readers to visit manufacturers and talk to them about their products. This should be balanced against independent research reports relating to specific or generic product types.

Compliance and performance monitoring

Whatever approach is taken to the use of innovative materials, components and structural systems, it is important to remember that compliance is required with the Building Regulations and appropriate Codes and Standards. And, once built and operational, it is important to monitor the performance of products in relation to the overall building performance. This applies equally to buildings constructed on site and to those produced in whole or in part in factories.

The Building Regulations and supporting guidance (*Approved Documents* in England and Wales, and in Northern Ireland; *Guidance Documents* in Scotland) are structured in such a way as to encourage the adoption of innovative approaches to the design and construction of buildings. This is done through setting performance standards, which must be achieved or bettered by the proposed construction. Acceptance of innovative proposals is in the hands of the building control body handling the application; thus, applicants must submit sufficient information on the innovative proposal to allow an accurate assessment of its performance. This is done by supplying data on testing, certification, technical approvals, CE marking and compliance with the Construction Products Directive (CPD), Eurocodes and Standards, calculations, detailed drawings and written specifications where appropriate.

Monitoring, testing and analysing the performance of new products and especially the overall performance of buildings are an important function. This has become particularly pertinent recently in our drive for carbon-neutral buildings and the use of many innovative approaches to design and construction. Although new building products and systems will have been tested by manufacturers under laboratory conditions, we can never be sure how they will perform in relation to the entire building, which will be subject to variations in local climate and patterns of use. Thus it is necessary to monitor and analyse the performance of buildings and to feed that information back to manufacturers, designers and constructors.

1.3 Product selection and specification

Both the quality and the long-term durability of a building depend upon the selection of suitable building products and the manner in which they are assembled. This applies to buildings constructed on the site and to offsite production. The majority of people contributing to the design and construction of a building are, in some way or another, involved in the specification of building products; that is making a choice as to the most appropriate material or component for a particular situation. Architects and engineers will usually specify products by brand name (a prescriptive specification) or through the establishment of performance criteria (a performance specification), which is discussed in more detail later. These choices are linked to the way in which the building is detailed and the process of construction, be it offsite or onsite. Contractors and subcontractors will be involved in the purchase and installation of the named product or products that match the specified performance requirements; that is, they will also be involved in assessing options and making a decision. Similarly, designers working for offsite manufacturers will also be involved in material and product selection; here, the emphasis will be on secure lines of supply and a transparent and ethical supply chain.

The final choice of product and the manner in which it is built into the building will have an effect on the overall quality and performance of the building. Traditionally, the factors affecting choice of building products have been the characteristics of the product (its properties, or 'fitness for purpose'), its initial cost and its availability. However, a number of other factors are beginning to influence choice, some of which are dependent on legislation, others of which are also dependent upon product safety (during construction, use and replacement/recycling and ethical resourcing) and environmental concerns as to the individual and collective impact of the materials used in the building's construction. Selection criteria will cover the following areas; the importance of one over another is dependent on the location of the product and the type of building project:

- Aesthetics.
- Availability.
- Compatibility (with other products).
- Compliance with legislation.
- Cost (whole life costs).
- Durability.
- Ease of installation (buildability).
- Environmental impact (low-carbon materials).
- Fire safety.
- Health and safety.
- Replacement and recyclability.
- Risk (associated with the product and the manufacturer).

For very small projects, it is common for contractors to select materials and products from the stock held by their local builders' merchant, choice being largely dependent upon what the merchant stocks (availability) and initial cost. For larger projects, there is a need to confirm specification decisions in a written document, the specification.

The written specification

Specifications are written documents that describe the requirements to which the service or product has to conform, such as its defined quality. It is the written specification, not the drawings, which defines and hence determines the quality of the finished work. The term specification tends to be used in the singular, which is a little misleading. In practice, the work to be carried out will be described in specifications written by the different specialists involved in the construction project. The structural engineer will write the specification for the structural elements, such as foundations and steelwork, whereas the architect will be concerned with materials and finishes. Similarly, there will be a specification for the electrical and mechanical services provision. This collection of multi-authored information is known as 'the specification'.

People from different backgrounds will use the written specification for a number of quite different tasks. It will be used during the pre-contract phase to help prepare costings and tenders. During the contract, operatives and the site managers will read the specification to check that the work is proceeding in accordance with the defined quality. Postcontract, the document will form a record of materials used and set standards, which is useful for alteration and repair work and as a source of evidence in disputes. In more recent projects this information will be held within the Building Information Models (BIMs), and will be accessible for maintenance and future repair work.

Specifying quality

Trying to define quality is a real challenge when it comes to construction, partly because of the complex nature of building activity and partly because of the number of actors who have a stake in achieving quality. The term quality tends to be used in a subjective manner and, of course, is negotiable between the project stakeholders. In terms of the written specification, quality can be defined through the quality of materials and the quality of workmanship. Designers can define the quality of materials they require through their choice of proprietary products or through the use of performance parameters and appropriate reference to standards and codes. Designers do not tell the builder how to construct the building; this is the contractor's responsibility, hence the need for method statements. The specification will set out the appropriate levels of workmanship, again by reference to codes and standards, but it is the people doing the work, and to a certain extent the quality of supervision, that determines the quality of the finished building.

Specification methods

There are a number of methods available for specifying. Some methods allow the contractor some latitude for choice and therefore an element of competition in the tendering process, while others are deliberately restrictive. The four specification methods are:

(1) *Descriptive specifying.* Where exact properties of materials and methods of installation are described in detail. Proprietary names are not used; hence, this method is not restrictive.

(2) *Reference standard specifying.* Where reference is made to established standards to which processes and products must comply, e.g. a national or international standard. This is also non-restrictive.

(3) *Proprietary specifying*. Where manufacturers' brand names are stated in the written specification. Here the contractor is restricted to using the specified product unless the specification is written in such a way to allow substitution of an equivalent. Proprietary specification is the most popular method where the designer produces the design requirements and specifies in detail the materials to be used (listing proprietary products), methods and standard of workmanship required.

(4) *Performance specifying*. Where the required outcomes are specified together with the criteria by which the chosen solution will be evaluated. This is non-restrictive and the contractor is free to use any product that meets the specified performance criteria. Performance specification is where the designer describes the material and workmanship attributes required, leaving the decision about specific products and standards of workmanship to the contractor.

The task is to select the most appropriate method for a particular situation and project context. The type of funding arrangement for the project and client preferences usually influences this decision. Typically, projects funded with public funds will have to allow for competition, so proprietary specifying is not usually possible. Projects funded from private sources may have no restrictions, unless the client has a preference or policy of using a particular approach. Obviously, the client's requirements need to be considered alongside the method best suited to clearly describe the design intent and the required quality, while also considering which method will help to get the best price for the work and, if desired, allow for innovation. In some respects, this also concerns the level of detail required for a project or particular elements of that project. Although one method is usually dominant for a project, it is not uncommon to use a mix of methods for different items in the same document.

It has been argued that performance specifications encourage innovation, although it is hard to find much evidence to support such a view. The performance approach allows, in theory at least, a degree of choice and hence competition. The advantage of one approach over another is largely a matter of circumstance and personal preference. However, it is common for performance and prescriptive specifications to be used on the same project for different elements of the building.

National Building Specification

Standard formats provide a useful template for specifiers and help to ensure a degree of consistency, as well as saving time. In the UK, the National Building Specification (NBS) and the National Engineering Specification (NES) are widely used. This commercially available suite of specification formats includes *NBS Building, NBS Engineering Services* and *NBS Landscape*. Available as computer software, it helps to make the writing of specifications relatively straightforward, because prompts are given to assist the writer's memory. Despite the name, the NBS is not a national specification in the sense that it must be used; many design offices use their own particular hybrid specifications that suit them and their type of work.

NBS Building is available in three different formats to suit the size of a particular project, ranging from Minor Works (small projects) to Intermediate and Standard (large projects). It is an extensive document containing a library of clauses. These clauses are selected and/or deleted by the specifier, and information is added at the appropriate prompt to suit a particular project.

With the uptake of BIM many specification decisions are tied to the product libraries held with the digital model(s) used by designers and specialist subcontractors.

Green specifications

The National Green Specification (NGS) is an independent organisation, partnered by the Building Research Establishment (BRE), to host an Internet-based resource for specifiers. It provides building product information plus work sections and clauses written in a format suitable for importing into the NBS, thus helping to promote the specification of green products.

Coordinated Project Information

Coordinated Project Information (CPI) is a system that categorises drawings and written information (specifications). CPI is used in British Standards and in the measurement of building works, the Standard Method of Measurement (SMM7). This relates directly to the classification system used in the NBS.

One of the conventions of CPI and Uniclass is the 'Common Arrangement of Work Sections' (CAWS). CAWS lists around 300 different classes of work according to the operatives who will do the work; indeed, the system was designed to assist the dissemination of information to subcontractors. This allows bills of quantities to be arranged according to CAWS. The system also makes it easy to refer items coded on drawings, in schedules and in bills of quantities back to the written specification. The main categories are shown in Table 1.1 (note there is no 'I', 'O' or 'Y'). The main sections are further divided into sub-sections.

Table 1.1 CAWS contents

A	Preliminaries
B	Complete buildings/structures/units
C	Demolition/alteration/renovation
D	Groundwork
E	In situ concrete/large precast concrete
F	Masonry
G	Structural/carcassing metal/timber
H	Cladding/covering
J	Waterproofing
K	Linings/sheathing/dry partitioning
L	Windows/doors/stairs
M	Surface finishes
N	Furniture/equipment
P	Building fabric sundries
Q	Paving/planting/fencing/site furniture
R	Disposal systems
S	Piped supply systems
T	Mechanical heating/cooling/refrigeration systems
U	Ventilation/air conditioning systems
V	Electrical supply/power/lighting systems
W	Communications/security/control systems
X	Transport systems
Z	Building fabric reference specification
	Additional rules – work to existing buildings
	Appendices

The introduction of the New Rules of Measurement (NRM) has brought a move away from CAWS to a new indexing system that aims to better reflect developments in building technologies (e.g. offsite and recycling). This numbered system contains 41 sections and no longer makes reference to CPI, as shown in Table 1.2.

Table 1.2 NRM2 contents

1	Preliminaries
2	Offsite manufactured materials, components and buildings
3	Demolitions
4	Alterations, repairs and conservation
5	Excavating and filling
6	Ground remediation and soil stabilisation
7	Piling
8	Underpinning
9	Diaphragm walls and embedded retaining walls
10	Crib walls, gabions and reinforced earth
11	In situ concrete works
12	Precast/composite concrete
13	Precast concrete
14	Masonry
15	Structural metalwork
16	Carpentry
17	Sheet roof coverings
18	Tile and slate roof and wall coverings
19	Waterproofing
20	Proprietary linings and partitions
21	Cladding and covering
22	General joinery
23	Windows, screens and lights
24	Doors, shutters and hatches
25	Stairs, walkways and balustrades
26	Metalwork
27	Glazing
28	Floor, wall, ceiling and roof finishings
29	Decoration
30	Suspended ceilings
31	Insulation, fire stopping and fire protection
32	Furniture, fittings and equipment
33	Drainage above ground
34	Drainage below ground
35	Site works
36	Fencing
37	Soft landscaping
38	Mechanical services
39	Electrical services
40	Transportation
41	Builder's work in connection with mechanical, electrical and transportation installations
	Appendices

Further reading

For information relating to specifications and construction information see: www.thenbs.com. See also www.greenspec.co.uk and www.bregroup.com for the Green Guide to Specification.

Reflective exercises

Your client is interested in non-conventional building materials and wishes you to specify your building project to be as ‘ecologically friendly’ as possible.

- ❑ What resources do you need to consult and why?
- ❑ List the potential advantages and disadvantages of changing from conventional building materials to non-conventional ones.

Offsite Construction: Chapter 2 AT A GLANCE

What? The term 'offsite' construction refers to the process of producing buildings, or parts of buildings, in factories remote from the building site. The manufacturing process is usually highly automated, resulting in prefabricated and pre-assembled components, panelised units (2D) and modular (3D, volumetric) systems. The prefabricated and pre-assembled units and modules are transported to site when required and craned into position on pre-prepared foundations or slotted into a structural frame. This is primarily a dry method of construction, although some wet trades may be employed to complete the building finishes.

Why? Offsite construction offers the potential to better control the quality of workmanship, remove the uncertainties associated with working in variable weather conditions on site, improve health, safety and wellbeing of workers, significantly reduce the amount of time spent working on the site, make financial savings through the repetitive production of units, and in many cases improve the environmental impact of buildings by reducing waste during fabrication. Offsite construction is ideally suited to buildings with a repetitive element, such as hotel bedrooms, housing and apartments, hospitals and schools. The techniques are also well suited to the pre-assembly of services, such as modular electrical cabling and services pods, elevators and staircases, and bathroom and kitchen pods. Producers of modular and system building offer a range of modules/elements that can be scaled from a small building to a very large development.

When? Using offsite fabrication changes the design and construction process. The design must be finalised before production starts and it will be necessary to work closely with the manufacturer. The design process is influenced by the possibilities and constraints of offsite production, which are specific to the technologies being used and the availability and suitability of companies that specialise in fabrication. The sequence of construction will vary depending upon the amount of prefabrication required, the type of building and site constraints. It is common to deliver the pre-assembled units when required to eliminate the need for on site storage and unnecessary handling.

How? The pre-assembled components, panels and modules will be manufactured in factories, usually to suit specific design requirements and with regard to manufacturing constraints. These pre-assembly factories manage the purchasing and handling of materials, production and delivery. Some manufacturers also offer an on-site assembly service. Off-the-shelf systems are available, in which case designers and engineers need to work within the constraints of the system. Once manufactured, the units are delivered to site, craned into position and connected to adjacent units and/or the loadbearing structural frame. Thus the construction skills, assisted with automation and robotics, are located primarily in a factory, not on the building site.

2 Offsite Construction

Construction is essentially a process of assembly, fixing and fitting of manufactured components in a precise location: the building site. The majority of components that make up buildings are factory produced (e.g. doors, windows, staircases and sanitary ware; bricks, blocks, tiles and standard sizes of timber, steel and concrete components). These are readily available from manufacturers' catalogues of standard products or may be produced to bespoke designs. Thus, what we refer to as building or construction is a little more akin to a process of assembly. It follows that moving the assembly process to a factory environment to create large 2-dimensional (2D) panels and 3-dimensional (3D) modules that can then be transported to site and craned into position is a logical development. Offsite is the term used to describe the pre-assembly of buildings and building components at a location, or locations that are remote from the building site. A wide range of terms are used in the construction sector, ranging from offsite manufacturing, fabrication and production, to industrialised building and industrialised construction, prefabrication, pre-assembled buildings and modern methods of construction (MMC), modular construction, modular building systems, volumetric construction and system build. More recently the term robotic construction has also started to be used to recognise the high degree of automation involved in offsite construction. Rapid prototyping and 3D printing (additive manufacturing) are also associated with offsite production techniques.

Offsite fabrication enables a high degree of accuracy (precision) and consistent quality of the component parts, be they panelised systems or volumetric systems (discussed below). These assemblies are then transported to the site to a precise timetable and erected in position in a clearly defined sequence. This is primarily a dry form of construction, with the majority of skilled trades being applied in a factory environment, free of the constraints of the weather. To undertake this process effectively and efficiently requires clear design decisions and planning input early in the design process. Component parts need to be accurately designed, as do the joints between, and attention must be given to fixing and positioning tolerances, as well as ease of access to the site. On a large, and usually highly repetitive, scale, offsite construction may prove to be a more cost-efficient alternative to more traditional site-based construction methods. For commercial applications, the saving in time on the site is an important economic consideration, allowing a faster return on investment and earlier occupation of the building. Improvements in accuracy, quality, environmental impact and health and safety are other important considerations when choosing offsite production.

Barry's Advanced Construction of Buildings, Fifth Edition. Stephen Emmitt.

Producing whole buildings, or parts of buildings as an industrialised process, is a logical technological development, but by no means a recent phenomenon. The early British settlers in America took prefabricated timber houses with them in the 1620s, and records show that prefabricated buildings of timber were exported from the UK for use in other countries. With the development of cast iron, and in particular the development of prefabricated cast iron components in the 1840s and 1850s, came the development of prefabricated iron buildings, with many prefabricated houses being shipped to Africa, Australia and the Caribbean. Concrete panel systems were developed during the 1900s, steel fabrication was developed in the 1930s and aluminium fabrication followed the Second World War in response to the housing shortage. Since this time the promotion and use of offsite systems has fluctuated, coming in and out of fashion due to a variety of political, economic, social and technical reasons. More recently the shortage of skilled tradespeople, combined with material supply chain challenges and advances in digital design and manufacturing has resulted in another push to establish offsite construction. A further driver is the commitment to climate action targets and the goal of delivering net zero buildings, which has further emphasised the need to modernise the way we build to reduce material waste. Now there is a wide range of systems available in the UK that are based on lightweight framing (lightweight steel sections and timber) and also concrete systems, primarily based on loadbearing precast panels. At the time of writing this book it is estimated that approximately 10% of buildings in the UK are delivered using MMC. The main concepts relating to cut timber, lightweight metal and concrete, and the extent of offsite production associated with each technology, are discussed later.

The extent to which construction activities are moved to a factory (or workshop) setting will vary depending on the type of prefabrication and pre-assembly employed. It will also depend on the ability to generate enough demand to make it economically worthwhile. In many respects, it is the volume housebuilding sector that has the most to gain (and lose) from using offsite production. Some buildings are assembled on site from factory-produced elements, while others are delivered to site as complete 3D volumetric units and craned into position, bolted to the foundation and then 'plugged in' to the services supplies. Offsite is primarily used for the new-build market, although the techniques and methods are equally suited to the refurbishment and upgrading of buildings, physical constraints permitting. Notable examples include urban regeneration schemes and the refurbishment and upgrading of existing concrete-framed housing units.

State-of-the-art manufacturing techniques offer many potential benefits to construction clients. It also offers designers and engineers the opportunity for creativity, something that was missing in much of the earlier offsite offerings. It is entirely possible for the design team to design a building using digital technologies and BIM platforms to collaborate with offsite manufacturers. The design can then be fabricated in the factory and delivered to site and assembled, with little need for a traditional contractor or trades. The groundworks and services connections can be procured using specialists, with the remainder done by the fabricating company. The design team provides the manufacturer with a precise digital model of the building, complete with material and performance requirements for every aspect of the design, including how it is to be assembled, maintained and disassembled. Advances in robotics provides the opportunity for process automation, reliability, and guaranteed quality. Offsite fabrication also claims to have environmental benefits compared to a more traditional approaches to construction, although detailed information can be difficult to acquire from manufacturers.

2.1 Functional requirements

Offsite pre-assembled buildings are no different to those constructed on site, in that they must comply with building regulations and associated legislation relating to, for example, fire safety, thermal and acoustic insulation, and environmental footprint. Thus the functional requirements of prefabricated buildings are the same as those identified for elements of site-constructed buildings as described in Barry's Introduction to Construction of Buildings and this volume. The only exception to this is a requirement for increased strength (bracing) of the floor and wall panels of volumetric modules to resist the different loads imposed on them during loading, transportation and positioning on the site. Tolerances are required to allow for the safe positioning of units and control joints are required to allow for thermal and structural movement.

The choice to use offsite construction, or not, needs to be made early in the briefing and conceptual design stages of projects. The decision will be coloured by the individual context of the project, client wishes, site constraints and economy. Aesthetics and many other factors that do not necessarily fall under the heading of technical or functional requirements will also come into play in the decision-making process. All of these have to be offset against the appropriate functional requirements, such as thermal performance and fire safety. A number of more generic advantages and disadvantages will also need to be considered in the context of each project.

Advantages of offsite

There are a large number of reasons why offsite production may be advantageous. Some of the most consistent arguments for moving construction process to the factory are related to the age-old challenge of attaining and maintaining quality. The quality of buildings relies to a large extent on the weather at the time of construction, the availability of appropriately skilled personnel to construct the building safely, and the control of materials used in the construction of the building. All of these factors are easier to control in a factory environment compared to the building site. Cost, both the initial cost and the life cycle costs, is also a determining factor. Although the initial cost of pre-assembled units and modules may be higher than their on site equivalents, they have to be considered against the speed of assembly and the time taken to make the building habitable, and in many cases income-generating. This can be easily offset the increased cost of the building system. Life cycle costs also need to be considered, especially the ease of maintenance and replacement. For factory-based production to be economic, the number of units or modules produced must be relatively large to cover the cost of tooling in the factory. The larger the scheme and the larger the amount of repetition, the greater the economic benefit to the customer. Similarly, the greater the repeated use of a design on other sites, the more cost-effective the process of production. This has to be balanced against architectural creativity and innovative solutions. More recently the opportunity to be creative has been realised through parametric and generative design, coupled with significant advances in robotic assembly and digital fabrication.

Control of working conditions

Quality control and validation takes place in the factory, helping to ensure a consistent level of quality. This helps to reduce the likelihood of time and cost overruns associated with poor quality identified during the snagging process and the time required to correct defects. Inclement weather usually leads to disrupted workflow and the possibility of inconsistent quality of work. Moving the majority of the work into a protected factory environment eliminates the uncertainties of the weather. With over 80% of the production process undertaken in a controlled indoor environment, the pre-assembled components remain dry during assembly. The flow of work is consistent and efficient, quality is constantly monitored and controlled, and operatives have a safe, controlled, working environment. Workers are not exposed to the uncertainties of the weather, there is better control of dust, pollutants and noise, and work can be planned to better suit the human posture resulting in, for example, less strain on the lower back.

Work on the site is much reduced. Panelised and volumetric units may be craned from the delivery vehicle directly into position on site, eliminating the need for on site storage. This operation can be achieved in most weather conditions (strong winds being an exception). There is less reliance on scaffolding and working at height, thus helping to improve the safety of workers on the construction site by reducing their exposure to risk. Because the majority of operations are conducted away from the site there is less noise, dust and disruption to neighbours of the site. There are also fewer tradesmen on site, and hence the possibility of accidents happening is much reduced. Combined, these factors result in the promotion of better health, safety and wellbeing.

Control of the quality of materials

Given the high volume of production, manufacturers are able to purchase large quantities of materials and are able to demand high-quality standards from their suppliers. Materials can be thoroughly inspected at the time of delivery to the factory and checked for compliance with the specification. All materials used are traceable as part of the ethical supply chain, providing the client with confidence that they are getting what they pay for. Such levels of material control are more difficult to achieve on buildings sites and it is difficult to prove that the contractor and subcontractors have used the materials that were specified. There is also less chance of theft of materials from the site, therefore site security can be reduced and may be required for a shorter period. Furthermore, the amount of material waste generated on the site (and sent to landfill) will be reduced, if not eliminated, with manufacturers recycling the majority of their waste within audited factory processes. The use of lean production, or lean manufacturing, techniques will also help to eliminate waste (both material and process) during assembly in the factory.

Control of environmental impact

Efficiency of the production process equates to less material waste, certainty over life cycle costs and guaranteed quality (less errors and less rework and hence less material wastage), and a traceable, ethical, supply chain. The production process offers energy saving measures and hence a reduction in carbon compared to the majority of construction activities undertaken on site. Material and process waste is minimised through the use of integrated design and manufacturing processes, resulting in very little waste material. The waste that is produced in the manufacturing and pre-assembly process can be easily recycled and not sent to landfill, as is often the case with site-based construction. Comparative savings in material waste have been estimated to be in the range of 75–90%. Life cycle management can be incorporated into offsite construction with the incorporation of asset tracking technologies (RFIs and QR codes) into all components. This allows asset tracking from design and production to operation, maintenance and recovery of components and materials at the end of its service life; usually linked to a BIM for the project. Because the supply chain is related to a manufacturer rather than individual projects it is much easier to manage the ethical supply chain, with complete traceability of materials. This allows the careful selection of material and component suppliers that meet strict ethical and environmental conditions. Many manufacturers have also provided systems that are relatively easy to deconstruct and recover at the end of the building's useful life and recycle with a minimal amount of waste, thus helping to create a closed-loop manufacturing system with a limited environmental impact. Although manufacturers claim that their systems are environmental friendly, it is not currently possible to obtain detailed information given the commercial sensitivity. Designers may need to make their own estimations of the embodied and operational carbon.

Control of time

With the majority of operations moved to the factory, the amount of time required on the site is much reduced. Groundwork for the foundations and services can be conducted in parallel to the offsite fabrication, ready to receive the pre-assembled components, panels and/or modules. For example, modules can be craned and slotted into a pre-prepared structural frame quickly and safely, resulting in a completed building in very little time. Less time on site also helps to limit disruption to the neighbours, with less noise and dust. The majority of modular systems rely on connection to pad or pile foundations, eliminating the need for strip foundations that are common in loadbearing masonry construction. Similarly, the careful grouping of services can save on pipework and connection costs (following an open building philosophy). Offsite testing and commissioning will further reduce the time spent on site. Skill on the site is required to manage the sequence of assembly, the craning and joining the pre-assembled components, panels and units together safely. In the majority of cases, scaffolding is not required, which is a considerable cost and time-saving, while also helping to improve safety. Defects can be dealt with in the factory using a zero defect approach, thus there should, in theory at least, be no problems at practical completion. Pre-assembled components that have been damaged in transit or by craning into position can be returned to the factory and replaced relatively easily and quickly.

Disadvantages of offsite

Offsite construction may not be the right choice for all clients, nor may it be appropriate for all projects and sites. Decisions to use offsite will be influenced by the site context, the type and scale of the building, and the wishes of the client, design team and contractor. Some builders and developers may also have economic and other business reasons to stick to a more site-based approach. For example, the cost of set up for the offsite manufacturing and transportation costs could override any cost and time savings for the project. Smaller house builders and contractors may prefer to use skilled labour to retain their employees, and speed of construction may not always be a primary concern. The more common reasons that may hinder the uptake and use of offsite construction include the following factors.

Physical access

Many construction sites pose physical and logistical challenges of ensuring unhindered and safe access, making the transportation and craning of large components very difficult or impossible. This is often a challenge for work to existing buildings and buildings in densely developed areas. It may not, for example, be possible to allow safe vehicular access to the site for the delivery of large volumetric units. Many sites also have significant challenges relating to town planning conditions, thus building in conservation areas or next to a historic building may mean that offsite is not an ideal choice because of limitations of aesthetics and scale.

Choice: supply and demand
Lack of choice may be a problem for some design teams, clients and developers, as the majority of offsite manufacturers offer limited ranges due to tooling and economy of production. In recent years the ability to expand the 'basic' range of 2D panels and 3D modules has been facilitated by advances in digital manufacturing, which has started to address some of the concerns over variety and aesthetics. In a similar vein, some clients may not relish the thought of being tied into a particular manufacturer for repair work and routine maintenance. This may relate to conditions of the warranty and/or may simply be linked to the technology employed and the availability of expertise to carry out the required work. A similar concern may be expressed for future extension and adaptation of modular buildings. There is also the issue of supply and demand to consider. Manufacturers of offsite panels and modules require a large and relatively steady flow of orders to ensure a profitable and hence a sustainable business. This continues to be challenging due to fluctuating demand and inconsistencies in economic outlook.

2.2 Offsite design and production processes

Offsite construction requires a change in how we think about the design and construction process. Emphasis moves to the early design stages and what is possible, and conversely what is not, in a factory environment. The site, with the exception of ground preparation and services provision, becomes the place where prefabricated components and pre-assembled units are assembled to form a building. In the majority of cases, the construction process is simplified, with less reliance on sub-contractors overseen by a construction manager.

Design for manufacture and disassembly

The term 'design for manufacture' (DFMA) is used to describe the philosophy of designing with factory production in mind. The design is tailored for ease of manufacture, transport, assembly, and at a point in the future, disassembly and materials recovery. This concept tends to rely on the use of standardised components and methods as part of a mass customisation process. Mass customisation is central to the realisation of competitive prices and short lead times from design approval (design freeze) to site delivery. Manufacturers' standardised component parts will be contained in a CAD or BIM library to help guide designers. This is referred to as a product family library.

Using offsite places greater emphasis on the need for the design team to collaborate with manufacturers as early as possible in the design process. The design of the building will be co-created in collaboration with the manufacturer(s), using the product family library, to create the most value for the client. Information will be co-created and shared via digital models, using 3D and BIM (nD) technologies and parametric design software.

Computer numerical control (CNC) production machines and computer-aided manufacturing (CAM) will use the digital files. Once the design has been agreed and signed off by the client, manufacturing can commence in parallel to ground preparation, site drainage and foundation work. This helps to deliver much shorter construction programmes compared to on site construction methods. Less time is spent on the site. This is an important concern for businesses and property owners keen to see the generation of revenue as quickly as possible. The digital files can be used as a reference source for maintenance, recording any changes during use and for disassembly at a later date.

Work is overseen by the production manager. The factory (or factories) is responsible for the ethical sourcing, purchasing, handling and processing of materials. Supply chains are product specific, not project specific, hence they are more stable than a typical construction project, allowing greater control of quality and cost. The production manager will work closely with the design team to agree the design, oversee production and plan the delivery and erection/assembly of the building. Design and production is usually based on producing assemblies that can be transported on lorries that do not need special licences or police notification prior to transportation. In the UK, lorries can pull trailers up to 18.3 m in length, 2.9 m wide and up to 2.9 m high. Route planning is required to avoid narrow roads and bridges with height and/or weight restrictions.

The amount of work required on the site will vary, depending on the type of offsite technologies being used and the characteristics of each site. This may range from the safe coordination of the delivery and assembly of fully finished modules, through to a more complex delivery and assembly process that involves the coordination of trades to complete external and internal finishes. Cranes will be required to move the components, 2D panels and 3D volumetric units from the delivery lorry and into position.

A typical production process

Given the repetitive nature of the manufacturing process and the high levels of capital investment, it is crucial from a business perspective that customer (market) needs are clearly identified and exploited by manufacturers of offsite. Research and development activities are concerned with market trends and technical (production) factors to ensure a profitable manufacturing process. The manufacturing process involves a range of highly skilled workers and robotic production. The extent of robotic manufacturing processes will vary between manufacturers; however, most manufacturers will follow a production process similar to that described here, with rigorous quality control conducted by trained personnel at the end of each step in the production process. The main steps in a typical production process are described here for a timber- or lightweight steel-framed unit:

- Discussion and confirmation of the customer’s technical specification (in relation to production capacity and production constraints).
- Planning and scheduling the manufacturing process, from ordering materials through to site delivery and hand over to the customer, is agreed prior to commencement of production.
- Automated pick up systems are used to coordinate production information and ensure that components are ordered from suppliers and delivered to the production line on time.

- Components are allocated to a specific project and supplied to the production line (approximately 3000 components may be required for an average-sized house).
- Main floor, ceiling panels and external wall panels are assembled (e.g. automated nailing, screwing and bolting of panels to joists).
- Frames are assembled in a box-shaped structure for rigidity (e.g. by automated spot-welding machines). Floor and ceiling panels are fixed to the frame, followed by the external wall panels. Fixing techniques vary but usually involve rivets, screws, nails, bolts, welds and glues. Joints between panels are filled using gaskets.
- Partition walls and services are installed in accordance with the specific requirements of the customer.
- Pre-assembled kitchen, bathroom and staircases are installed at the factory.
- Painting and finishes are completed (if required).
- Final quality control check before the modules are protected with packaging (to avoid impact damage and to protect from moisture and dust) prior to shipping.
- Units are loaded onto trucks by large forklifts or cranes and transported to the construction site in accordance with the customer's delivery date.
- Units are then craned onto pre-prepared foundations and joined together using horizontal and vertical fixings (bolts) to provide structural rigidity. Roofing units are delivered at the same time as the modules, craned into position and fixed.
- Interior finishing work (if needed) is completed.
- Final quality control check before the completed building is handed over to the client.

Selecting a manufacturer

Before investing in offsite construction, potential purchasers (specifiers) should:

- visit the factory to see how the units are assembled, the quality control methods in place and the degree of flexibility available in the construction of the units (physical layout and choice of materials).
- check the experience and financial stability of the manufacturer, ask for and take up references, check independent reports (if available); do not rely solely on the promotional material produced by the manufacturer.
- look for independent approvals. Check that the modular building system has been accredited by the British Board of Agrément (BBA); International Organization for Standardization (ISO) approval should apply to the whole process; functional performance has been independently tested and endorsed (e.g. for quality, fire, acoustic insulation, thermal insulation and air leakage, and structural stability).
- speak to fellow architects, engineers and contractors to gain feedback on their experience with a particular manufacturer. What went well? What could have been done better?
- if applicable, investigate how the modular system will interface with traditional construction techniques and/or existing buildings.
- visit some of the built schemes. How are they weathering externally and standing up to use internally? What do the clients and users think, based on their use of the buildings?
- as with all other decisions about building components and products, try to consider at least three manufacturers and compare them to see who offers the best overall value for the given context of the site and client.

Logistics and transportation
Manufacturers will provide detailed transportation plans and delivery information to ensure the pre-assembled components and units can be delivered to site when required. It is not efficient to deliver components to site and store them, nor may it be practical. The pre-assembled components and units should be scheduled to be delivered to a 'just-in-time' schedule. This will involve route planning (height and width restrictions) and a detailed lifting and positioning plan in relation to the proposed reach capacity of the crane(s) to be used. This will also involve coordination with the master programme for the project.

2.3 Pre-assembly

A wide range of terms and definitions exist in relation to offsite methods. The most commonly known terms are used in this book.

On site pre-assembly

There are some situations where pre-assembly is undertaken at, or immediately adjacent to, the construction site. The term 'on site' prefabrication or pre-assembly is used to describe this activity. Sufficient space is required around the proposed building to allow for safe and efficient pre-assembly activities to take place. This is sometimes done in the open, but more commonly is carried out under the protection of a temporary structure, the field factory. Examples may include the casting of concrete components for positioning in the building and the pre-assembly of timber components, such as roof trusses, for subsequent craning into position. This technique is not common, but it may be useful where access to the site for large construction components and the vehicles on which they are transported is not possible, or the shear size of the project lends itself to a field factory approach.

Sub-assemblies and components

Sub-assemblies and components cover a wide range of familiar sub-assemblies and components. These would include familiar sub-assemblies and components such as doors, windows, staircases and balconies manufactured in factories (see *Barry's Introduction to Construction of Buildings*). More recent innovations include prefabricated reinforcement cages and mats, and precast foundations.

Prefabricated reinforcement cages and mats
The fixing of reinforcement bars (sometimes referred to as 'rebar') on the site is a labour-intensive activity. Many of the positions in which the reinforcement is laid and tied require stress of the workers' posture. Fixing reinforcement also poses a risk to health and safety of the workforce. Moving this activity to the factory allows the reinforcement cages and mats to be made in conditions where the working conditions can be controlled and hence the workers' posture and health and safety can be addressed. The resultant cages and mats can be delivered to site and quickly positioned by crane, considerably reducing the amount of time spent on site by labourers. Reinforcement mats can simply be rolled out, fixed into position and the concrete poured onto them.

Prefabricated foundations
The use of driven piled foundations removes the need for mass excavation of the site: this can save time and limits the amount of ground works. The development of brownfield sites is an example where it may be necessary to limit the amount of disturbance to the ground because of ground contamination. The use of driven piles and bored displacement piles removes the need for soil excavation and disposal that would be needed for traditional foundations. Prefabricated foundations also reduce the problems associated with working around wet concrete foundations. As soon as the piles are driven into the required position, the pile caps can be positioned and prefabricated foundation beams craned into position. Prefabricated units can then be delivered and positioned on the foundations. If the modular units are sufficiently strong in their construction, the foundation beams can be omitted; thus, the modular units sit on and span between, the pile caps.

Panelised pre-assembly (2D)

Panelised systems are also referred to as 2D systems or non-volumetric pre-assembly. The term 'flatpack' is also used. Panels are used for the construction of walls, floors and roofs, in conjunction with a structural frame. Panels are produced in two forms, either as uninsulated panels (termed 'open') or thermally insulated panels (termed 'closed'). Panels are relatively easy to manoeuvre and fix on the site using cranes and site personnel. Once the units are fitted together, the corner finishing pieces are attached and the units sealed. Effective fitting of prefabricated units relies on the use of sealants between individual panels to create an airtight seal.

Prefabricated panels range from simple unfinished wall, floor and roof panels to fully finished panels and cassettes.

- ❑ Open wall and roof panels with skin on one side only. Uninsulated floor panels comprising exposed joists or beams with floor decking only to the upper face.
- ❑ Thermally insulated open and closed wall, roof and floor panels finished on both sides but without surface finishes.
- ❑ Thermally insulated closed wall and roof panels finished on one side (internal or external face, depending on the design). Floor panels will be finished on the upper or lower side.
- ❑ Thermally insulated closed wall, roof and floor panels finished on both sides and including the integration of mechanical and electrical services. Wall panels also include doors and windows. Roof panels also include roof windows. These panelised systems are sometimes referred to as 'enhanced' panels because of the level of finishing.

The word 'cassette' is used to describe a floor or wall or roof panel. Cassettes are usually closed systems with built-in lifting straps. They are fully insulated and include service runs. Timber roof cassettes allow clear spans of up to 12 m by incorporating engineering joists. Metal cassettes also allow long clear spans, the structural support provided by lattice cross-section joists built into the cassettes. Panels and cassettes are designed and produced to be loadbearing so that they can be joined on site to create usable space. They can also be used in conjunction with a structural frame.

Volumetric (or modular) pre-assembly (3D)

Volumetric and modular pre-assembly are terms that tend to be used interchangeably to describe the process of making large parts of buildings, or entire buildings, in a factory. Volumetric is used to describe the enclosure of space, hence the term 3D modules. Fully complete modules will include wiring and plumbing, surface decoration, fixtures and fittings. In some cases, they may also include furniture. Modular bathroom and toilet pods and plant rooms are well-suited to modular pre-assembly. Volumetric units include bedrooms, kitchens, bathrooms and toilet pods . The size of the units is limited by transportation, with 8×3.6 m being a typical size. Completed modules are transported to site and positioned by crane on a pre-prepared foundation or slotted into a structural frame. Rarely is there any need for scaffolding or on site storage facilities, allowing for rapid assembly and completion of the project on site. The typical range includes the following, ranging from the most simple to the most complete modules:

- ❏ Modules with surface skin to inside or outside face only and no thermal insulation (the insulation and finishes are added on site).
- ❏ Thermally insulated modules with skin to both sides but no surface finishes.
- ❏ Thermally insulated modules with the inside or outside face finished.
- ❏ Modules with finishes to both sides, complete with thermal insulation and integration of services, windows and doors.

Modular building is one means of helping to achieve efficiency, reduce wastage of materials and deliver improved quality of the finished product. Some specialist commercial applications, such as chains of hotels, supermarkets and fast food outlets, have exploited factors such as time and repetition of a particular style (associated with brand image) particularly well to make prefabrication and modularisation work for their business needs. For commercial applications, the slight increase in initial build cost can be offset against savings in time and longer-term savings in the repetition of units. Supermarkets, hospitals, schools, airports, hotel chains and volume house builders have successfully used modular construction techniques.

Economic advantages are achieved with projects that have long runs of identical modules. For smaller developers, the speed of construction may not be their primary concern; however, other factors such as more consistent quality and improved working conditions may be determining factors.

Logistics is a major consideration when constructing buildings using large volumetric units. Once assembly has been completed in the factory the modules need to be labelled and temporarily stored, often in a protected environment to prevent damage from the weather, until they are required on the site. Each unit is labelled so that it is clear where they belong in the assembly sequence for the building, and stored so that they can be delivered in the correct order. To reduce demands on storage, 'just-in-time' manufacturing processes may be used. This means that the units are completed just before they are required on site, which reduces demands on storage, although any unexpected delays at the factory or during transportation will result in delays on the site. Consideration must be given to the sequence of lifting the modules into or onto the structural frame or building, and also to safely manoeuvring them into their final position. Clear access must be maintained to ensure the modules are not damaged during the lifting and positioning process. If scaffolding is being used, it must be designed to allow adequate space for access.

Hybrid systems (2D and 3D)

Combining panelised (2D) and volumetric (3D) systems is known as a hybrid system. An example would be a development that uses a flatpack design along with volumetric modular bathroom pods. Combining several different techniques can help to resolve design challenges that the use of one technology (system) cannot achieve in isolation. Coordination is required to ensure compatibility between the systems, both in terms of their constructability and their long-term durability.

Modular building services

Building services is one area of construction that can benefit in a major way from prefabrication and pre-assembly. A considerable part of building services is repetitive work. Many components can be pre-assembled and grouped together, for example horizontal pipework, vertical risers, complex wiring systems, pre-wired and assembled electrical installations (light fittings, switches, heating units, etc.).

It is beneficial to do as much as possible of the assembly of services offsite in clean and controlled environments. While it may not be possible to prefabricate long runs of cables and pipes that have to be fed around the building, it is possible to assemble the fixtures, fittings and plant. This has led to the development of innovative jointing and fitting systems to ease assembly and future replacement, repair and disassembly work. It is also becoming common to break services down into units that can be delivered as discrete modules. Plant rooms with boilers, air handling units, power terminals and connecting cables and pipework can be made up offsite in structural frames, tested, then transported to site and lifted into place, where they are subsequently commissioned for service (Figure 2.1). Photograph 2.1 shows an example of a standard steel frame structure fitted out with prefabricated bathroom and toilet pods as part of a hotel development.

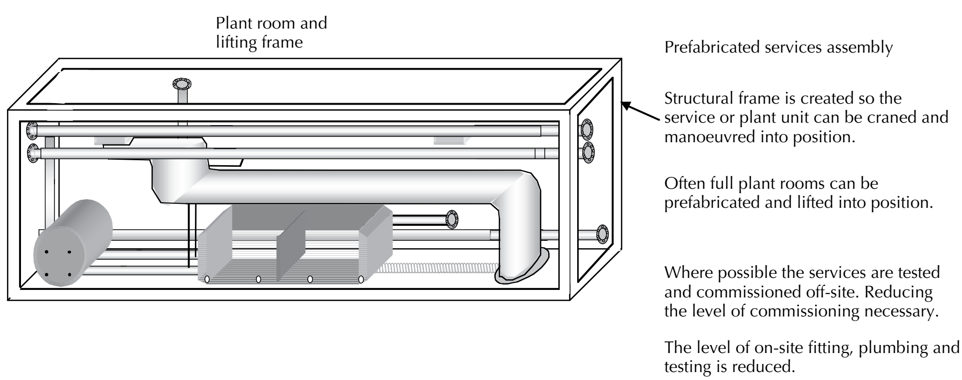


Figure 2.1 Modular building services.

Standard panels and units are stored ready for delivery.

Panels can be assembled around a frame or can form a self-supporting structure.

Photograph 2.1 Framed construction with prefabricated bathroom and service pods.

2.4 Joints and joining

Whatever offsite system is chosen, the quality and performance of the completed building will depend upon the way in which the unit is attached to the foundations and how individual modules and panels are joined together. Structural integrity of the whole building relies on the way in which the joints are designed and how the pre-assembled components and units are positioned and fixed to one another on the site. Acoustic performance needs careful consideration to avoid direct and indirect sound transition through structural frames and/or fixings. Acoustic insulation is usually achieved with the use of double-layer walls and floor that are designed to be acoustically isolated, hence reducing unwanted sound transmission. Similarly, the fire resistance of the completed building will be affected by the integrity of joints and associated fire and smoke stopping in cavities and at junctions. Most modules are designed with fire resistance of 30–60 minutes, which can be increased if required.

Tolerances

Tolerances are crucial to the final quality and durability of the building. The three interrelated tolerances to consider are manufacturing, positioning and joint tolerances:

(1) *Manufacturing tolerances*. Factory production methods are capable of producing components, panels and modules to very precise dimensions. These are dimensionally consistent, regardless of how much product is required. Manufacturers will provide full details for their product families.
(2) *Positional tolerances*. Maximum and minimum allowable tolerances are essential for safe and convenient positioning and assembly. The specified tolerance will depend upon the size of units being manoeuvred and the technologies employed to position the units. It is important to ensure that all units are positioned without damaging them or their neighbouring units. Consideration needs to be given to the reach of cranes.
(3) *Joint tolerances*. These will be determined by the materials used in the construction of the units, which determine the extent of thermal and structural movement; the size of units and their juxtaposition with other units. The design of the joint will impact on performance requirements such as air infiltration, sound attenuation and thermal properties. The sealing of the joint after assembly will be instrumental to the long-term durability of the building.

Site work and connections

The setting out and construction of the foundations must be carried out accurately since there is no (or very little) room for error. This applies to modules that are placed and bolted directly onto the foundations and also to the erection of the structural framework to house a number of modules. Accuracy also applies to the positioning of utilities connections such as electricity, gas, mains water and waste drainage. Modules are usually bolted to a ground beam, directly to the foundation, or directly to the structural frame, after which the service connections are made and subsequently tested. Manufacturers provide detailed information relating to their particular system; however, it is common for structural connections to be made in both the horizontal and vertical planes to ensure structural integrity. Most systems rely on bolted connections and/or self-tapping screws. Metal modular systems usually incorporate welded connecting plates to the modules to allow them to be bolted to the structural frame and/or adjacent module. Timber modular systems are usually constructed on a steel subframe, to which metal shoes are welded to allow the module to be bolted to the foundation connection. Some system manufacturers also include cover plates to provide protection to the joint between modules (which are usually sealed with expanding foam prior to the cover plate being fixed). Other systems rely on sealing with a flexible weatherproof sealant, or a bespoke cover to suit the design of the building.

2.5 Prefabricated housing

Offsite production methods have long been used in housing. In the UK, the most common systems are based on precut timber, lightweight metal and to a lesser extent precast concrete. Hybrid systems utilise the benefits of two or more materials, for example, a steel subframe onto which a framed timber module is assembled. The range of designs and cost ranges from high-end bespoke individual housing to larger housing developments and apartment buildings. More recently the mass housebuilding companies have moved towards offsite modular systems, either investing in their own production facilities or partnering with manufacturers and suppliers of modular systems.

Pre-cut timber systems

Timber was the first material to be used for prefabrication, being readily available and easy to work in the factory with large machines and on site with hand-held tools. Timber also has the advantage of being easy to work (repair) if damaged in transit or during construction. A variety of systems that encompass varying degrees of factory production are available from manufacturers located in the UK, Europe and North America. These range from the fully built factory house, delivered to site and craned onto suitable foundations, to the 'kit-of-parts' which are assembled on site by hand and are popular with self-build (DIY) and self-help schemes.

The advantages of timber systems relate to the thermal properties of timber, the fact that there is no waste (all 'waste' can be recycled), the ease of handling, working and fixing, and the relative ease of repair and replace. The disadvantages tend to relate to the uniqueness of the manufacturer's system and the associated difficulties of extending or altering the loadbearing structure. Given that timber is relatively lightweight, care needs to be taken with the detailing and fixing to prevent the unwanted transmission of sound to adjoining properties. Attention to detail is also required due to the potential reduction in thermal insulation around timber studs. Further information on timber and structural timber frames can be found in Chapter 5 of this book.

The Segal self-build method

The architect Walter Segal developed a simple method of construction based on timber frame construction and modern materials, specifically for self-help community building projects in the UK. The Segal method is based on a modular grid system that uses standard sizes of building materials as supplied by builders' merchants. The timber frame is built off simple pad foundations, which are dug at existing ground levels to avoid the need for expensive site levelling. Once the structural frame has been erected the roof can be constructed, walls completed and services installed. The lightweight and simple design allows both men and women to build their home (individually or as part of a cooperative group) using simple tools and with limited knowledge or experience of building. This dry construction method eliminates what Segal called the 'tyranny of wet trades' (plastering, bricklaying, etc.) and forms a lightweight, adaptable, ecologically sound building that is designed to suit the requirements of the users (and also the builders). Considerable cost savings are possible due to savings on labour and, to a lesser extent, materials due to the simplicity of the design.

Volumetric timber-framed units

Volumetric production of timber units has been greatly assisted by developments in IT (especially building information modelling), allowing the production of a large variety of standard house types and providing the means to computer-generated bespoke designs. As a general guide, the timber-framed houses built in a factory use 20–30% more material in the framing than those framed on the site. This is to ensure safe lifting and transportation. The additional cost of the material is offset against time and labour savings. The majority of factories will glue and nail or screw the components together to form a solid, volumetric, assembly. The main principles used are those outlined in Chapter 5. The main difference is that it is easier to control quality in the factory and the whole building assembly can be kept dry during manufacture, transportation and positioning, thus significantly reducing concerns about the moisture content of the timber. Photograph 2.2 shows a panel of a timber-framed house being assembled under factory conditions. These panels are then joined together to form a modular unit.

Photograph 2.2 Factory production of a timber-framed house. Insulation and windows installed (a); exterior timber cladding being fixed (b).

Metal systems

Lightweight steel is the material most used for metal-framed units. Advantages and disadvantages are not so different to those for cut-timber systems. The advantages of metal-framed volumetric units include the possibility of zero waste in manufacturing, the capacity for long clear spans, ease of handling and fixing, and easy to repair and replace. The disadvantages tend to relate to the uniqueness of the manufacturer's system and the associated difficulties of extending, altering and replacing the metal components. Given that steel is relatively lightweight, care needs to be taken with the detailing and fixing to prevent the unwanted transmission of sound to adjoining properties. Attention to detail is also required due to the potential reduction in thermal insulation around the metal frame. Further information on steel and structural steel frames can be found in Chapter 6 of this book.

Steel-framed housing
A typical steel-framed modular housing development would comprise a 75 mm deep galvanised steel frame with insulation and vapour barrier sheathing similar to a timber framed module. Wall frames are delivered with integral bracing, which are easily placed into position. Floor joists are usually 150 mm deep 'Z'-sections that are attached to the wall panels. The roof structure is assembled at ground level and lifted into place in one piece. The windows and doors can be screwed to the steel frame before the external finish, for example, brickwork, is constructed.

Modular steel framing
Volumetric house construction comprises steel-framed modular units that may be joined together to form semi-detached and terraced units. The pitched roof is also prefabricated and craned into position. Average construction times are between 6 and 8 weeks for a house, with the steel frame taking around 3 days to erect. The steel frame construction comprises cold-formed lightweight steel stud sections, commonly 75 mm deep galvanised steel framing members, which are sheathed in insulation on the external face and finished with fire-resisting board on the inside face of the wall (thus creating a panel construction). The wall frames include integral steel diagonal cross-bracing members and are designed to be easy to manoeuvre and fix on site. Floor construction typically comprises 150 mm deep steel joists fixed to a Z-section element attached to the wall panels. Windows are installed on site and the external cladding (usually brickwork) is built on site once the frame is complete. Advantages include quick construction, dimensional accuracy, and long-life and long-span capabilities (thus allowing for future adaptability). The modules and materials are also relatively easy to recover and recycle at the end of their service life.

Concrete systems

Concrete panels have been in use since the early 1900s in the UK. Concrete is cast in large moulds and the reinforced units transported to site before being craned into position. Early pioneers would cast the concrete on site, but with concerns over quality control and efficiency, the casting of units has now moved to a few specialist factories where quality can be carefully controlled and the casting process made cost-effective. Some of these units may be made from standard mould shapes and are effectively available off the shelf; others are designed and cast to a special order. The completed units are then delivered to site to suit the contractor's programme and are lifted into position using a crane.

Considerable investment is required in making the moulds, and the units are heavy for transporting and positioning. More recent developments have been in the use of lightweight reinforced concrete units; however, there is still a large amount of work required on site to finish the concrete units, and this can add considerable time to the site phase. Reinforced concrete frames (rather than structural panels) can be used to provide the structural support for modules or pods, which are craned into position. It is, however, more usual for a steel frame to be used.

The advantages of concrete are largely associated with the material's inherent properties of high thermal mass, good sound and fire resistance and its loadbearing capacity. Disadvantages are associated with the material as it is heavy and awkward to manoeuvre, and it is difficult to make changes during and after construction. For example, drilling holes into the panels for services produces waste (if the holes are not pre-formed in the factory). Care is also needed to avoid thermal bypasses at junctions, and a high degree of finishing may be required on site. Further information on concrete and structural concrete frames can be found in Chapter 7 of this book.

Concrete and steel hybrid systems

Modular building is suited to small, inner city and urban sites. Several hybrid systems are available that use a combination of materials. Typical examples are modules constructed of steel and concrete, bolted together and clad in brickwork or stone to suit the streetscape and provide variety to different projects. Closed panel timber systems, with windows, doors and insulation can be combined with roof and floor cassettes and beam and block floors. There is plenty of variety available. U values of 0.15 $W/m^2 K$ are easily achieved for external walls and roofs (or ceilings) with thermally insulated cassettes.

2.6 Additive manufacturing (3D printing)

The term 'rapid prototyping' is used to describe techniques that allow the fabrication of a building component or assembly using digital files and 3D printing. This technique allows manufacturers and design teams to quickly and cheaply produce a scale model of a prototype prior to full-scale production. The rapid development of 3D printing technologies also makes it possible to produce full-scale building components from additive manufacturing techniques. Components and buildings are printed directly from digital data files that are contained in 3D models. A technique similar to inkjet printing on paper. The technique relies on 'printers' producing artifacts by adding one layer of material to another to create the whole; hence the term additive manufacturing. Other terms such as direct digital manufacturing and freeform construction are also used. Material is sprayed from a nozzle to 'print' buildings and building components, ranging from simple to relatively complex shapes. Typically, this is carried out in factories due to the large size of the printers, but it is possible to use very large printers on the construction site with the print heads travelling along scaffold to print materials in consecutive layers. Materials used range from concrete and cementitious materials, clay, mud, plastics, polymers and nylon to metals. These comprise organic, non-organic and composite materials such as fibre-reinforced polymer (FRP), along with reclaimed and recycled content materials, all with varying environmental footprints. The main characteristic of the sprayed materials is a low viscosity so that they can be pumped through the printer head. Along with many other innovative approaches to construction these techniques are promoted as environmental friendly given the low level of construction waste generated in the construction process. Some of the materials used have a better carbon footprint than others.

There are four main approaches to additive manufacturing as given below:

(1) *Concrete printing.* The materials used are cement-based mortars and gypsum using a wet process. The material is sprayed through a nozzle to build up layers of material into walls and other features. Reinforcement is required to provide tensile strength to the artifact. There are limitations with this approach because of the slow curing process, although this has not stopped manufacturers from printing concrete houses using recycled construction materials comprising glass fibre, cement and additives. Concrete printing may be used to produce components without using formwork, which is known as freeform construction. There is a saving in materials and time as there is no need to construct a formwork or mould.

(2) *Contour crafting (*CC*).* Contour crafting is a rapid prototype or 3D printing process to fabricate large components and full-scale structures. These are generated from digital data. Extrusion nozzles are housed on robotic arms on a gantry and controlled by computer software to quickly produce large structures, such as houses, by printing a quick-setting material.

(3) *D-shape printing.* The D-shape printing process involves a large 3D printer that prints objects in layers. The printer mixes sand with an inorganic liquid (seawater) and a magnesium-based binder to produce objects with a stone-like appearance.

(4) *Direct metal laser sintering.* This process relies on lasers precisely heating layers of powdered metal material until it forms into a solid mass. This process can produce components with an extremely fine level of detail and accuracy.

Subtractive manufacturing

Some manufacturing techniques rely on removing material, such as routing machines and laser cutters. This is known as subtractive manufacturing and the two most common techniques are:

- *CNC router and CNC milling machines.* A CNC router is a computer-controlled machine that can be used for cutting hard materials such as timber, steel, plastics and composites. The cutting is controlled from a 3D digital file. A CNC milling machine works in a similar way, using rotary cutters to remove material from the surface of a hard material. Both machines enable a high level of detail to be achieved.
- *Laser cutting.* This technique involves firing a laser to melt, burn or vaporise material to cut or engrave a design from a digital computer file. Materials that can be cut and engraved range from wood sheets to acrylics and plastics.

Further reading

For additional information on modern methods of construction (MMC) see; www.designingbuildings.co.uk; and for steel systems see Steel Construction Info: www.steelconstruction.info.

Reflective exercises

This reflective exercise relates to your current design project, regardless of its location, size and intended use.

- ❑ What aspects of the building could be fabricated offsite. How would this influence your design and why would you decide to use offsite construction for the project?
- ❑ What benefits does offsite fabrication offer (i) the client, (ii) the design team and (iii) the builder? Justify your thinking.
- ❑ Are there any challenges with using offsite fabrication for your design project?
- ❑ How could offsite fabrication impact the environmental impact of your building project?
- ❑ What is the likely impact on embodied carbon and operation carbon?

Pile Foundations, Substructures and Basements: Chapter 3 AT A GLANCE

What? Pile foundations are columns that are driven or cast into the ground to provide a supporting framework for the building to rest on. Steel and concrete columns, known as pile foundations, can be inserted (driven) or bored into the ground, transferring the building loads to loadbearing strata. Hardwood timber may also be used or piles, especially for temporary low-rise buildings. 'Substructures' is a term used to describe a variety of work that takes place below ground level to form supporting structures and basements.

Why? It is common for framed buildings to bear onto piled foundations, especially when the loadbearing strata is a considerable depth below the surface of the ground. Substructures and basements provide additional space within the building footprint. In situations where it is not possible to build high, for example, in semi-urban or rural areas, it may be possible to provide additional space under the building, subject to ground conditions and town planning restrictions.

When? The piles are placed or driven into the ground early in the construction process. This ensures any local ground disturbance caused by the piling does not affect other works, for example, site drainage. On sites that have previously had buildings on them, it is common practice to identify and remove existing foundations or to avoid them when placing the piles. Substructure works and the construction of basements are usually one of the first tasks to undertake to ensure a logical flow of work on the site. Adding a basement to an existing building is likely to have an impact on adjacent buildings and foundations.

How? There are a variety of piling techniques available, the choice of one over another largely dictated by ground conditions, the building design and appropriate physical access for machinery to conduct the piling. Basements tend to be constructed of reinforced concrete or dense concrete blocks, which is then tanked to prevent water and damp from entering the building.