The parts are then moved together (b) and given appropriate dimensions. The actual forms and plans are given in (c) and (d).
A significant anniversary for computer-aided design (CAD) passed in 2013, without much notice in the architectural world. In 1963 Ivan Sutherland, then a PhD candidate at the Massachusetts Institute of Technology (MIT), submitted his thesis on the ‘Sketchpad’ system, one of the most influential doctoral dissertations ever presented.

With additional developments by Timothy Johnson and others, Sketchpad contained in embryo most of the features of CAD systems as they have developed over the intervening 50 years. It had the first ever graphical user interface. It allowed both 2D drafting and 3D modelling of designs – the latter displayed not just in wireframe, but with hidden lines removed. It allowed simulation of the performance of designs, for example calculations of the behaviour of engineering structures, or predictions of flows of current through electrical circuits. And Sketchpad was also linked directly to MIT’s numerically controlled milling machines in the world’s first integrated CAD/CAM system.

Five decades after Ivan Sutherland first launched ‘SketchPad’, computer-aided design has entered the engineering mainstream. That strand in architectural computing which pursues the potential of generative design systems has, however, followed an entirely different course. Here Philip Steadman, Emeritus Professor of Urban and Built Form Studies at the Bartlett Faculty of the Built Environment, University College London (UCL), criticises such approaches, and instead argues for a ‘design science’ that lays out worlds of possible plans and forms from which designers can choose.

Generative Systems for Automated Plan Layout
All these features of Sketchpad – drafting, 3D modelling, simulation of performance, links to component manufacture – have become mainstream in architectural computing, even if some of them took decades to filter through from engineering and product design. What Sketchpad did not try to do was to generate designs. It was conceived rather as a tool for supporting designers. In architectural computing, by contrast, there was much interest from the outset in generative design systems, and in particular methods for the automated layout of plans. Several programs were developed in the 1970s for producing layouts in which the total amount of pedestrian movement would in theory be minimised. These were conceived very much within the functionalist paradigm that pervaded the ‘design methods movement’ of the 1960s, and drew on techniques borrowed from operations research and mathematical programming. Typically, surveys were made of movement patterns in existing buildings of the relevant type, to give numbers of journeys between rooms of specified function. Various systematic methods were then deployed for assembling and rearranging spaces so as to minimise total travel. There were three major problems.

First was the questionable assumption that the patterns of trips observed in existing buildings would be reproduced in new buildings with different layouts. Arguably, geometry and movement are interdependent rather than independent of each other. Second, because of the goal of minimising movement, the methods tended to produce deep concentric plans clustered around the most highly connected spaces. Third, and most important, was the fact that a single criterion of performance was used to generate designs. Subsequent work tried to introduce constraints related to other considerations such as lighting and orientation, and such efforts continue today. But the tools have rarely, if ever, been taken up in practice.
Exhaustive Enumeration of Small Rectangular Plans

Other methods for producing room layouts by computer developed at this time might have appeared superficially similar, but were in truth based on a diametrically opposite philosophy of design. It came to be appreciated that, if consideration was confined to rectangular rooms in rectangular packings, and the number of rooms was not large, it was possible to enumerate all possible arrangements exhaustively. Bill Mitchell, Robin Liggett and I developed the first of these methods in the mid-1970s. At the heart of our system was a complete listing of ‘rectangular dissections’ (rectangles cut into rectangles) represented as configurations without dimensions. The rectangles stood for rooms. The catalogue could be searched for arrangements conforming to given sets of criteria, capable of meeting specified limits on the sizes and shapes of rooms, adjacencies between rooms, and orientations of rooms to points of the compass. The method produced all arrangements meeting the given specifications. These might be plans and rooms of simple overall rectangular shape. Alternatively, the use of dummy spaces could create L-shapes, U-shapes and so on.

The important point is that this approach did not search for some single supposedly ‘optimal solution’. On the contrary, it laid out entire fields of possibility within which architects have free rein. Should they elect to confine themselves to a rectangular geometrical discipline of this kind, however, they have no other choices. Ulrich Flemming developed a program called DIS (‘dissection’) in the late 1970s that produced essentially the same kinds of results. Frank Brown and I carried out a number of exercises with DIS, two of which can illustrate its power.

After the First World War, the British Local Government Board published a Manual setting out standards, for the first time, for publicly funded housing. The publication included plans for two-storey semi-detached ‘working men’s cottages’. These were ‘only for general guidance’ and were ‘not intended to hamper initiative or to prevent full expression to local customs and traditions’. The Manual also gave a series of highly specific recommendations as to the types and sizes of rooms to be provided, their spatial relationships and preferred orientations for rooms. Brown and I entered all the requirements relating to the Manual’s ‘south-facing parlour house’ into DIS. The program produced just one layout, the very plan published in the Manual.

It is clear that the Manual’s authors had no idea that they were limiting designers who followed their recommendations to a unique solution. It seems likely that they had designed the ‘model’ plan first, and then taken off its dimensions and spatial relationships and turned these into their design guidance. For recommendations relating to other house types in the Manual, DIS produced small numbers of possible options. In general there are trade-offs between the severity of the specified constraints and the numbers of resulting plans. It might have been useful to policy-makers and their architects to know about these trade-offs. Results from DIS are shown here for the first-floor plans of semi-detached houses with a 6-metre (20-foot) frontage, under plausible constraints on room sizes and relationships. Only two of these possible plans were widely used in practice in the 1930s, when millions of semi-detached houses were built in England. When all constraints are relaxed, the fields of possibility can become very large.
One weakness of both the Mitchell/Steadman/Liggett method and Flemming’s DIS system was that they required users to specify circulation spaces and limits on their sizes at the outset, instead of allowing them to be introduced in response to the placement of ‘habitable’ rooms. In the 1980s, Flemming developed the LOOS program (named after the Austrian architect), which overcame this problem by enumerating loose packings of rectangles with gaps into which circulation could then be inserted.7

Shape grammars came from a very different intellectual tradition – Chomskian linguistics – and have generally been applied to the study of questions of architectural style and composition. It is worth noting all the same that a shape grammar is defined as the universe of all designs that can be produced from a given set of shape rules. That universe can be large and is not generally laid out for inspection. Nevertheless, in the case of the first architectural shape grammar, devised for Palladian villas by George Stiny and Bill Mitchell, all possible villa plans based on 3 x 3 and 5 x 3 grids were enumerated by similar methods to those used for counting rectangular dissections. Again these are configurations whose dimensions are assigned by the rules of the grammar.8

There is, however, a fundamental and insuperable limitation on the scope of these methods for enumerating possible plans. This is the ‘combinatorial explosion’ that causes the numbers of arrangements to grow rapidly with increasing numbers of component rooms, to the point where complete catalogues of plans with more than 10 or a dozen rooms would become astronomically large. Flemming’s DIS system pushed this limit somewhat by generating only those arrangements that conformed to a specified constraint set, but the basic problem remained. Practical applications of the approach were thus confined to small houses or other buildings of similar size. Bill Hillier took this to mean that architecture was not, after all, an \textit{ars combinatoria.}9 But his conclusion was premature.

\textbf{Enumeration of Built Forms: An ‘Archetypal Building’}

It is certainly true that no complete enumeration can be made of arrangements of larger plans if these are represented at the room scale. But this is a matter of the level of representation. If we are prepared to move to a higher level of abstraction, and consider not individual rooms but zones within buildings, then an approach by enumeration becomes feasible again. I have been experimenting over the last 10 years with a method for representing built forms made up of ranges, wings and courtyards in different configurations.10 These are all cut from a larger ‘archetypal building’ as shown in the illustrations here.

Dimensions of the various parts are not specified at the outset. The numbers of courts and storeys are arbitrary: there could be more. The space in dark grey is day-lit from the exterior or from the courts. The space in light grey is artificially lit. The archetype thus embodies the constraints on form of some elementary ‘generic functions’ of architecture, in particular those of lighting. Simpler built forms approximating to real buildings – an 18th-century hospital, a 20th-century block of apartments – can be cut from the archetype by selecting ‘strips’ of accommodation, ‘strips’ containing courts, and floors, and moving these together. The parts can then be given appropriate dimensions (see pp 24 and 25).

There is no space here to go into the technicalities, but it is possible to enumerate all built forms that can be generated from the archetypal building by means of a method of coding, whereby every strip that is retained is coded with a 1, and every strip that is removed is coded with a 0. This produces two strings of 0s and 1s, an \(x\) string and a \(y\) string. Putting these together gives, for the nine-court archetype, a 30-digit code in each case. All these codes are binary numbers. The sequence of all binary numbers produces all possible selections and permutations of strips, hence all possible plans. The combinatorial problems are now quite manageable again: with the removal of duplicates by symmetry and some other redundant codes, the number of possible plan forms generated from the nine-court archetype is 1,745,655.

\textbf{An ‘Architectural Morphospace’}

For visualisation, it is convenient and informative to lay out all these plans across a two-dimensional space. Here the \(x\) strings of the binary codes are plotted on the \(x\)-axis, and the \(y\) strings on the \(y\)-axis, so that each plan is mapped to a unique location. It turns out that plans of similar shape are clustered together within rectangular or triangular zones; so, for example, the part of the space nearest the origin contains zones for simple rectangular plans, L-shapes, U-shapes, single courts and so on. Notice two points. These are generic plan shapes, each of which can occur in many variants depending on the presence of day-lit and artificially lit strips. And once again they are undimensioned shapes: each part can be assigned any desired size. This is what in biological morphology is termed a ‘morphospace’ or space of possible forms. In biology and architecture we can expect to find real organisms or real buildings respectively at different locations within morphospaces.

I have plotted the plans of 19th-century ‘pavilion’ hospitals, English elementary schools, and Chicago and New York office skyscrapers across this architectural morphospace. They turn out
Philip Steadman, An architectural ‘morphospace’ produced from the archetypal building, 2014

top left: The plans are all encoded with strings of 0s and 1s in the x and y directions. The x strings are plotted on the x-axis of morphospace, and the y strings on the y-axis. Each plan is thus mapped to a unique location. Plans with the same generic shapes are clustered within triangular or rectangular zones as shown. Many variants of each shape occur, depending on the numbers and arrangements of day-lit and artificially lit strips.

Philip Steadman, The area of morphospace closest to the origin, 2014
top right: This is where simple rectangular plans, Ls, Us, single courts, Ts, Hs and X-shapes are found.

Philip Steadman, The two (heavy) lines in morphospace on which the plans of the ward blocks of 19th-century ‘pavilion hospitals’ are found, 2014

The lines correspond to two plan types: with wards on one side of a central circulation spine, as in Henry Currey’s St Thomas’ Hospital, London, 1865–71 (centre right), and with wards on both sides of the spine, as in Douglas Galton’s Herbert Hospital, London, 1861–5 (bottom right).
to lie on particular lines as a result of their characteristic cross-sections and arrangements of day-lit space, artificially lit space (corridors) and courts. The morphospace, that is to say, effects a formal classification. The courtyards of the archetypal building can be filled with ‘halls’ to represent, say, the central assembly halls of late 19th-century Board schools, or the top-lit entrance halls and atria of office blocks. Generic formal properties of plans can be mapped across morphospace as, for example, bilateral and diagonal symmetries. The circles in the figure shown here plot a number of 19th-century schools: their architects gave them all plans with bilateral symmetry.

Standard dimensions can be assigned to the various parts of all plans in morphospace, for example dimensions of depth in the day-lit strips sufficient to allow daylighting, typical corridor widths for the artificially lit strips, minimum dimensions for courts and so on. It is then possible to compute different dimensional properties of the resulting forms, such as the ratio of volume to wall area. This is a quantity that we might expect in general to have a bearing on heat loss and on the costs of construction. Another such property is floor space index (FSI – the ratio of floor area on all floors to site area), an indicator of the densities achievable with different forms. Measures of circulation distances would also be possible. Notice that these are objective geometrical measures of built form, not predictions of people’s activities. They can give an (admittedly crude) indication of the relative performance of different built form options, whatever the particular behaviour of the eventual occupants.
There are many limitations to this architectural morphospace in its present form, and I make no claims for comprehensiveness. The forms of many actual buildings can already be represented. But the scope is confined obviously to a rectangular geometry, and beyond that there are further restrictions on the classes of rectangular built form that can be represented. Extension to the third dimension would, however, be straightforward, allowing for forms with different numbers and types of floors. I would emphasise that this is a first attempt at mapping worlds of possible built forms at this level of abstraction, one that could be greatly developed. The purpose is to contribute hopefully to architects’ strategic knowledge of these worlds – knowledge that they can then deploy in design. Trade-offs between different aspects of performance can be studied, as against allowing the computer to ‘optimise’ plans on one or a few criteria, as in the early layout methods and in some more recent systems employing genetic algorithms.

Might practitioners be interested in this kind of activity in ‘architectural science’? The work on enumerating room layouts of the 1970s had little impact on practice, partly because at that time the idea that options for design might be limited by intrinsic geometrical factors was an unpalatable one. My own belief is that, since these limits indubitably exist, it is better to understand them and their consequences. Such knowledge is not constraining, but liberating.

Notes
10. Philip Steadman, Building Types and Built Forms, Troubador (Leicester), 2014; see also www.buildingtypesandbuiltforms.co.uk.