Replication protocol analysis: a method for the study of real-world design thinking

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Given the brief of an architectural competition on site planning, and the design awarded the first prize, the first author (trained as an architect but not a participant in the competition) produced a line of reasoning that might have led from brief to design. In the paper, such 'design replication' is refined into a method called 'replication protocol analysis' (RPA), and discussed from a methodological perspective of design research. It is argued that for the study of real-world design thinking this method offers distinct advantages over traditional 'design protocol analysis', which seeks to capture the designer's authentic line of reasoning. To illustrate how RPA can be used, the site planning case is briefly presented, and part of the replicated line of reasoning analysed. One result of the analysis is a glimpse of a 'logic of design'; another is an insight which sheds new light on Darke's classical study of 'primary generators'.

Keywords: methods of design research and teaching, design replication, case study, design decisions, inference patterns

The nature of architectural design has attracted considerable attention among researchers, both as a subject of study in its own right, and because the development of computer systems for design support necessitates a better understanding of the design process.

As a contribution to the continued exploration of architectural design we have refined Porter's replication technique into a method which we call 'replication protocol analysis' (RPA). To illustrate the use of RPA, we have undertaken a case study of architectural site planning. Our aim is to present RPA as a practical tool for design research and education; to
demonstrate the feasibility of RPA for the study of full-scale real-world designing; and, in so doing, to provide insights into the nature of design thinking.

We expect our results to be of interest to readers concerned with research into the nature of designing or with development of design support systems, and to readers who study or teach design. For example, in a context of design psychology or cognitive science, (pilot) studies using the relatively resource-economic RPA method may lead to results which are either of interest in their own right, or can lead to the formation of hypotheses to be tested using other, more labour-intensive, methods. Furthermore, results of our case study, or similar ones also based on RPA, may inform the development of knowledge-based systems for decision support, in particular of the early phases of design. Last but not least RPA could probably be of use to students of architecture as a supplement to traditional design studio projects, or as a mental exercise to designers who wish to stimulate their own professional development.

After the section below, in which we describe RPA as a method of inquiry and justify our use of it, we present the case in section 2 and analyse it in section 3. In section 4 we summarize the contributions made.

1 Presentation and discussion of the RPA method

In his book *How designers think*, Lawson\(^5\) remarks (pp 226–227) that ‘there are really only a few basic approaches that can be taken to design research’, namely: 1) artificial experiments under controlled conditions; 2) observation of designers in action; 3) analysis of interviews with, or the writings of, designers; and 4) simply thinking about design. Lawson finds all of these approaches to have serious shortcomings. The RPA method is closest to Lawson’s third category, but involves, as described below, a specialized kind of ‘writings’ by a designer who is not identical with the originator of the design. Thus RPA may not match exactly what Lawson had in mind, but his criticism of category-three methods seems to apply to RPA as well. The problem with such methods, Lawson says, is that the designers may tend ‘to “sell” their ideas rather than explain their methods’, and even if they try not to, one cannot be confident that their description ‘is accurate reporting as opposed to post-hoc rationalization’.

In an attempt to solve this methodological problem, we recommend RPA as a method deliberately designed *not* to yield ‘accurate reporting’ on the designer’s method, but rather to document a train of thoughts which is guaranteed to include a ‘post-hoc rationalization’ of the design. In our view designers’ ability to rationalize what they or other designers do is not

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an obstacle to design research, but a source of insight well worth exploration.

In the subsections below, we present the RPA method, compare it to a different but related and well-known method, design protocol analysis (DPA), which belongs to Lawson's category two (observation of designers in action), and explain the importance we ascribe to rationalization.

1.1 RPA step by step
The RPA method comprises five stages which can be stated in general and practical terms as follows. Stages a) and b) are understood to be carried out more or less in parallel. Stages c) and d) may be omitted in cases where they are not deemed relevant to the purpose of the investigation, or where the resources to include them are unavailable. The RPA method requires substantial knowledge about the kind of designing under scrutiny; the person doing the 'replication' (the replicator) should have some experience in that area of design.

a) Study carefully a given design brief and a given 'target' solution (not designed by yourself) to the problem posed by the brief (using, for example, the brief and a project proposal of a published architectural competition)
b) Without communicating with the originator(s) of the solution, try to replicate a line of reasoning you think might have led from the given brief to the given target solution. (It may stimulate thinking to work in a small group, or to explain your reasoning to another person as you go along.) Record the results while they are being produced, or shortly after, with or without accompanying sketches but always in the form of a coherent argumentative text, the replication protocol. In the protocol you describe a sequence of design decisions sufficient to account for the progress from brief to target solution. Include the most convincing reasons you can think of for each decision. Where appropriate, include alternative design decisions and reasons for giving up those not maintained in the final design
c) (Optional) Repeat stages a) and b) with the same brief and one or more other target solutions
d) (Optional) Repeat stages a), b) (and possibly c)) with the same brief and target solution(s) but with one or more different replicators
e) Analyse (and compare) the resulting replication protocol(s) using whatever concepts and methods that are suitable for the purpose of your inquiry.

Stages a) and b) above constitute a variant of the 'design replication'
technique proposed by Porter and used by him to study the (possible) reasoning behind two designs: one for redesign of Copley Square in Boston, MA; the other for a building for The American Academy of Arts and Sciences. Porter, however, made transcripts of tape recordings to document his replications—a technique we do not recommend, because it tends to produce loosely structured and verbose material. Stages c) and d) are included to suggest ways of enriching the protocol material, although in this paper we shall consider only a single replication (stages a) and b)), and illustrate some ways in which it can be analysed (stage e)).

1.2 Replication protocol analysis versus design protocol analysis

The category-two method we call DPA is known in the literature simply as protocol analysis. It has been used for quite some time in design research, for example by Eastman, Akin, Eckersley, Schön, and by Goldschmidt. Protocol analysis as used by these authors involves studying a protocol (sketches, notes, audio or video recordings) of a subject’s behaviour when designing. As opposed to such recording of the actual design process, the protocol produced by replication represents what Porter calls ‘some idealized design process that, knowing where it began . . . and where it was heading . . . moved in that direction with great efficiency’ (p 170). Hence our distinction between design protocol analysis (DPA), and replication protocol analysis (RPA).

Obviously DPA yields a relatively authentic picture of the design process, as opposed to RPA. A replication protocol should never be read as a description of the actual design process. However, as Porter points out, replication may be of interest all the same, provided it offers a plausible account of what actually happened; and, we add, unless it is essential to obtain a record of a ‘genuine’ design process, RPA offers distinct advantages over DPA:

- If the ‘replicator’ is identical with an investigator who is to analyse the protocol, the investigator is a priori intimately familiar with the material he or she is to investigate.
- The replication itself gives a deep insight into both brief and target solution. If, as recommended, the replication compares alternative decisions along the way from brief to solution (stage b) of the method), or if multiple replications are made (stages c) and d)), a good insight may also be gained into the space of possible solutions. Such insights could be valuable in research as well in education.
RPA can be used without the need to inconvenience practitioners.

A replication protocol is likely to be much more understandable than a design protocol because it is a result of an explanation process, not a by-product of a design process. Replicating an argument leading from brief to design solution naturally lends itself directly to exposition in a written medium, possibly illustrated with sketches, whereas asking a designer to externalize his or her design thinking in writing as it proceeds, is inconceivable. As Lawson observes in his criticism of category-two methods (which include DPA), the verbal and graphical utterances of the designers may not be coherent, unless we also know what goes on in their heads, and ‘as soon as we ask them that we have destroyed the very situation we are observing’; and if we try to avoid this by recording design group conversations, ‘the situation remains artificial and the data requires considerable interpretation’ (p 226).

Recently, further criticism has been levelled against DPA by Davies who studied the design behaviour of expert computer programmers.

Complex real-world designs can be studied by RPA, as exemplified by Porter’s work and by the present paper. DPA, on the other hand, requires video or audio recording for the designer to concentrate on designing, but this necessitates the transcription of tapes for subsequent interpretation and analysis. Asking a practicing designer or a design team to ‘think aloud’ while working on a real project, which may take weeks or months to complete, is absurd; and even if some extremely obliging and patient designer should agree to do so, the resulting amount of raw data to transcribe and interpret would be prohibitive.

1.3 Imagining versus reasoning: on the applicability of replication

To clarify for what purposes RPA may be used, let us turn once more to Lawson (pp 101–102). Psychologists, he says, have classified thinking in various ways, including the dichotomy into imagining and reasoning, ‘both of which are obviously needed in design’. As opposed to pure art, design ‘is directed towards solving a real world problem’, and, Lawson continues, ‘this does not mean that imaginative thought can be excluded from the design process but that its product will probably always need evaluation by rational thought in order that the designer’s work should be relevant to his real-world problem. The control and combination of rational and imaginative thought is one of the designer’s most important skills . . .’.

In keeping with this contention of Lawson’s – as we interpret it – we assume as a basis for our discussion that:
Design thinking is composed of interdependent activities of ‘imagining’ and ‘reasoning’ (and others, e.g. remembering, which are not our concern).

‘Imagining’ in design is used for design evolution, i.e. proposal of tentative decisions (possibly including decisions to reject earlier decisions).

‘Reasoning’ in design is used for design rationalization, i.e. justification of tentative decisions ‘by rational thought’ (which may or may not include ‘evaluation’ in the sense of preference of one option over another).

To summarize metaphorically this understanding of the nature of design thinking, we might say that evolution and rationalization are to design thinking what sail and rudder are to a sailing boat. It should be stressed, however, that we consider design evolution and design rationalization to be equally important aspects of designing. Discussing them in artificial isolation, as we shall do for clarity of exposition, might, if no further comment were made, conceal our conviction that in reality they are intertwined and interdependent, presumably stimulating and prompting each other.

Probably it is possible for an experienced designer to proceed mainly by imaginative thought, relying on his or her experience to know that the decisions made could be rationalized, should the need arise. But even then it follows from our assumptions that gaining insight into the nature of design rationalization is to gain insight into an important aspect of designing (see note 1).

With RPA we can study design rationalization, not that of designers designing, but of designers acting as replicators. The underlying assumption is that a replicating designer’s post-hoc justification of other people’s work is not different in nature from the same designer’s (post-hoc) justifications of his or her own work. (Note that we do not base our confidence in RPA on any assumed similarity between the replicator’s reasoning and that of the originator of the design under scrutiny.)

Furthermore, the justifications recorded in a replication protocol convey design knowledge about the kind of artefact in question. Thus, with a suitable analysis of the replication protocol, RPA is what in artificial intelligence circles is known as a method of knowledge elicitation. Its characteristic feature is that one elicits design knowledge, not from the originator of the design but from another person (the ‘replicator’) whose
mind is stimulated for that purpose by the given design brief and the target solution(s).

Although it is less obvious, we contend that RPA can also be used to some extent, for the study of design evolution – notwithstanding the fact that the replicator’s thinking is biased by the target solution(s). We base this (perhaps somewhat controversial) statement on the following reasons:

- The replicator invents a sequence of decisions, albeit with known target(s), but in doing so exercises a kind of creativity needed in genuine design evolution.
- In particular if the replicator explores a branching sequence of decisions with ‘dead ends’ representing alternative design options, or if the replicator is prompted by target solutions to criticize them or suggest ideas for alternative solutions, elements of creative design evolution are involved.
- The act of justifying design decisions with respect to the goals set out in the given design problem leads to an increased understanding of the problem, and quite likely to augmentation of it with new goals as well as recognition of hidden relationships and constraints. The same kind of ‘problem evolution’ is, presumably, an integral part of genuine design evolution.

Hence RPA has some potential for the study of design evolution as well; at the very least a potential for formation of tentative hypotheses which can be tested by other, more labour intensive methods.

2 The Spangsbjerg case

Our case study was based on the design brief of an architectural competition arranged by the municipality of Esbjerg, Denmark, concerning the conceptual design of a site plan for a residential development in Spangsbjerg, at the outskirts of the city of Esbjerg. One ‘target solution’ to guide our replication was chosen from among the published summaries of design proposals submitted for the competition. Several of these were interesting, but to keep the replication work within reasonable bounds we selected a single proposal by the architectural firm Arkitektgruppen i Århus, which – rightly, in our opinion – was awarded the first prize (see note 2). Though not used as ‘target solutions’, the other proposals may also have influenced the replicator’s work, in particular his considerations of alternative design options.

The Spangsbjerg case seemed attractive to us for a number of reasons: It is, presumably, representative of modern site planning, at least in
2.1 Design brief

The design brief of the competition is fairly elaborate but the most important points can be summarized as follows. There are five explicitly stated purposes:

**Purpose 1:** to propose a site plan which offers a diversity of dwelling types, located in low-rise high-density buildings and detached single-family houses, and which accommodates an old people’s home and dwellings designed particularly for elderly people, closely associated with the normal dwellings.

**Purpose 2:** to fit the project in naturally among the surrounding areas of detached houses, but so that the site is somewhat more heavily utilized than the surrounding sites.

**Purpose 3:** to create a varied and stimulating environment through the design of buildings and areas for play and other open-air activities.

**Purpose 4:** to create a traffic system which works well, where it is easy to find one’s way, and which gives priority to the safety of nonvehicular traffic.

**Purpose 5:** to enable a stage-wise construction over several years, such that the area constitutes a harmonic whole at each stage.

Furthermore, contextual and other constraints were imposed on the solutions:

**Site characteristics:** The site is shaped roughly like a parallelogram, some 740 metres (in the direction SW-NE) by 260 metres (in the direction NW-SE). The surface is largely flat, and the soil of normal load-bearing capacity.

**Existing and planned features:** Windbreaks in the form of straight rows of trees exist along the borders, and also on the interior of the site, mainly in three belts along the long sides, placed almost regularly at intervals of...
approximately 70 metres (see note 3). The old people's home is to be located near the SW corner of the site (on a specified area). A bicycle and footpath is planned along the SE border.

**Use types and distribution:** About 50% of the area should be used for social housing (rentable flats) and 40–60 dwellings for elderly people, and the remaining about 50% for privately owned houses. The first category should be designed as low-rise high-density, the second as a mixture of low-rise high-density and detached houses. Privately owned houses designed as low-rise high-density can be legally organized as 'shared ownership housing' (see note 4). Dwellings of the various kinds should be grouped into clusters of limited size. Clusters of privately owned houses, including shared ownership housing, should allow for extension of each dwelling to 120 m². A nursery home for 40 children aged 0–6, and a club for 40 adolescents must also be provided.

**Car park capacity (cars per dwelling):** Social housing: 1.5. Dwellings for the elderly: 1.5 (one in-curtilage parking space). Private detached houses: 2 (in-curtilage). Low-rise high-density dwellings (including private homes) with mass parking (if any): 1.5. Nursery home and club together needing parking space for 12 cars.

**Vehicular traffic:** Cars can have access along the SW border (where no more than two entry points are allowed, including the driveway giving access to the old people's home), and close to the northern corner (one entry point allowed at either the NW or the NE border).

**Pedestrian traffic:** It appears from the maps provided that pedestrians can enter the site along the SW border except where this is occupied by the old people's home, and at or near the northern and eastern corners.

**Building mass and utilization ratios:** The maximum number of dwellings (not counting the old people's home) is estimated to 320 (limit negotiable, not mandatory). Tentative maximum building height: 1½ storeys (negotiable). Tentative maximum local utilization ratio (of gross floor area to area of occupied land): 35% for areas of low-rise high-density dwellings; 25% for each individual curtilage of a detached house (both limits negotiable).

### 2.2 A design solution

Figures 1 and 2 show prize-winning proposals from the Spangsbjerg competition. The existing windbreaks which have been almost completely preserved, are clearly visible in Figure 1: the rows of trees along the site.
Figure 2  Axonometric view from first prize design entry for Spangsbjerg site planning competition, showing a portion of the central street with a plaza, and surrounding formations of courtyard buildings and detached houses

border, and three more rows running in the longitudinal direction of the site. Along the central row of trees a pedestrian street with three 'green' plazas have been built, framed by relatively tall coherent buildings. Outside this central 'spine' there are lower buildings organized around courtyards, or separately as detached houses; some of the latter with access from a common 'green'. Vehicular access is via roads along the two rows of trees next to the central one (in the 'border zones'), with mass car parking at suitable intervals. An old people's home mentioned in the brief above is seen in the SW corner.

3 Applying RPA to the Spangsbjerg case
We have now presented our case: a design problem and a solution to it, both authentic examples taken from practice. (By now the project has actually been built, in a somewhat modified form.) Section 3.1 gives an excerpt from the replication protocol in which our 'replicator' (the first author who was originally trained as an architect) developed a line of reasoning that might have led from the problem to the solution. He first orally explained his thoughts to the second author, then went over them

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again alone and in more detail, recording them in writing as shown, and
drawing on notes made by both of us during the first iteration. Small
examples of how the protocol can be analysed will be given in sections
3.2-3.4

3.1 Replication protocol
In the following excerpt from our replication protocol, paragraphs are
labelled with their original numbers for reference. (The protocol in
extenso is available in a working report22). References to replication
protocol paragraphs will be of the form [rep. <paragraph number>]. To
prepare our analysis, we have augmented most of the replication para-
graphs with a list of decisions explicitly or implicitly made there. (The lists
were not part of the original protocol). We distinguish two kinds of design
decisions: a forward decision is one intended to lead towards a completed
design (say, a decision on shape, use, composition, or organization); a
backward decision is a decision to reject one or more forward design
decision(s). Only if marked as such in the lists, are decisions ‘backward’;
otherwise they are ‘forward’.

A decision involves the preference of one option over one or more
alternatives. In the protocol it is often the case that only the preferred
option is mentioned. However, ‘backward decisions’ testify occasional
consideration of alternatives, discarding options that were not preferred
after all, and inaugurating a new train of thought. (Recall that in the
description of RPA, stage b), we encourage explicit consideration of
alternatives.)

2) The windbreaks seem to be about the only characteristic feature of
the whole place, cutting up the site lengthwise into four narrow strips
about 70 metres wide. So probably we should try to preserve them, if
we can.

3) They are terribly regular, though: straight and uniform, with the
exception of the second row of trees (counting from NW, including
the borderline rows) being broken into two, slightly offset, pieces.
But the longitudinal direction is stressed. The brief says traffic will
enter at or near the short sides. So the main traffic flow will obviously
also be longitudinal. That seems to go well with preserving the
primary windbreaks. (There are also some secondary ones orthogon-
al to the longitudinal direction, but they are rather randomly
scattered around, and I wouldn’t mind having to sacrifice them.)
[Decision 3a: Preserve primary windbreaks.]

4) We can think of the four strips of land and the windbreaks as figure
and ground, respectively, or vice versa. [See note 5].
5) Suppose the strips are ‘figure’. What would that suggest? – Some kind of relatively independent units, probably, separated by the trees. For example, in the two central strips we might have low-rise high-density along a kind of ‘street’, and in the two outer strips low private houses along a road.

[Decision 5a: Let strips between windbreaks be ‘figure’.]  
[Decision 5b: Separate independent units by the trees.]  
[Decision 5c: Place low-rise high-density streets in the two central strips.]  
[Decision 5d: Place private houses along roads in the two outer strips.]  

6) In this way we might obtain a good fit to the neighbouring areas (purpose no. 2), and the buildings might be constructed one strip at a time (purpose no. 5). But presumably, the outer strips would look much like the trivial roads with detached houses on either side of the site, so perhaps the fit will be a bit too perfect! Also, the independent units imply that each strip will be served by a traffic system of its own. If pedestrians and cars are mixed, safety will be difficult to achieve (purpose no. 4). And if they are separated, it means we shall have eight channels of traffic (four times two). Which is far too much.  

[Decision 6a (‘backward’): Give up strips-as-figure (decisions 5a–5d).]

7) Now let’s suppose the strips are ‘ground’ so the trees become ‘figure’. Instead of dividing things, the trees should unite them. How can the trees ‘unite’ groups of buildings? – by playing the role of avenue trees! Of course, a traditional avenue would need a double row of trees, but a single will do as well. [. . .]

[Decision 7a: Let strips between windbreaks be ‘ground’.]  
[Decision 7b: Let windbreaks ‘unite’ as avenue trees.]  

8) For the avenues to work properly as uniting elements, they should serve as the main access areas for the adjoining buildings. These, in turn, should be oriented with their fronts towards the avenues, and preferably overlook them.

[Decision 8a: Let avenues be main access areas for the buildings.]  
[Decision 6b: Orient building fronts towards avenues, overlooking them.]

[. . .]

15) So the pedestrians will use all three avenues. (As well as the path already planned along the NE border). We cannot have three or four routes for pedestrians running in parallel for the full length of the site (approximately 740 metres) without interconnections. The area must be ‘permeable’. Therefore the avenues (and the path) should be connected at reasonable intervals by secondary paths allowing pedes-
trians to pass from one to the other.

[Decision 15a: Connect the three avenues and the footpath with interconnections at reasonable intervals.]

...]

31) To ensure affinity with the existing neighbouring areas, one might simply use a similar organization with detached houses with private gardens along a road, possibly a little taller than the existing ones to ensure a smooth transition to the spine (purpose no. 2).

[Decision 31a: Organize detached houses in border zone traditionally along a road, as in existing area.]

32) But too much of this will be monotonous. What can be done to introduce more variety?

[Decision 32a (backward): Give up decision 31a.]

33) The brief requires two or three legal categories of housing (see ‘Use types . . .’ [section 2.1 above]). In order of increasing ‘privacy’ they are: social housing, ‘shared ownership housing’ (optional), and ordinary single-family houses. We might give each legal category its own physical expression to create variety [a quality also required by the brief, see ‘purpose no. 3’]. But how?

[Decision 33a: Give each legal housing category its own physical expression.]

34) Social housing, the least private category, naturally belongs in the spine, with access from its street and plaza spaces which are fully ‘public’. The ‘shared ownership housing’ could be located in separate, somewhat lower, buildings around a courtyard. A courtyard is also a ‘public’ space, but less so than the street and plaza, because there is no through traffic. Such courtyard structures can be placed in the border zones, with an entrance to the courtyard facing a border avenue. And the rest of the border zone can be used for low single-family detached houses which offer the highest degree of privacy, each being surrounded by its own garden.

[Decision 34a: Place social housing in spine street buildings.]

[Decision 34b: Place somewhat lower ‘shared ownership housing’ around courtyards in border zones.]

[Decision 34c: Place privately owned dwellings in low detached houses in border zones.]

3.2 Sample analysis: design rationalization

To illustrate one way a replication protocol could be analysed with respect to rationalization, let us briefly suggest how certain patterns of reasoning underlying the protocol can be revealed. (The method of logical analysis used here, and its application to a much larger portion of the Spangsbjerg protocol, have been described in detail elsewhere23,24)
Consider the simple forward decision 33a: ‘Give each legal housing category its own physical expression’ which is motivated by its ability ‘to create variety’ as required by the brief. In a schematic argumentative form reasoning in this part of the protocol can be rendered as follows:

A) If each legal housing category is given its own physical expression, then variety is created

B) It is required that variety is created

C) Hence it is desirable that each legal housing category is given its own physical expression.

To conclude from A) and B) that ‘it is required that each legal housing category . . .’ etc., would be going too far, as obviously there are other ways of creating variety. But clearly the motivation of decision 33a establishes the desirability of the stage of affairs expressed by statement C), on the grounds that the decision contributes to variety.

The notions of desirability and ‘requiredness’ are central to the argument as outlined above; but they are not expressible in standard logic. However, in various systems of so-called modal logic25 we find the modalities of permission and obligation, or those of possibility and necessity, to which desirability and requiredness can be considered analogous. In a framework of modal logic, we might formalize the pattern of reasoning behind the above argument as follows:

\[
\begin{align*}
\text{From} & \quad M \rightarrow E \\
\text{and} & \quad \text{Required } E \\
\text{conclude} & \quad \text{Desirable } M
\end{align*}
\]

where the arrow designates implication (if-then), italicized capital letters are variables standing for ordinary propositions (like ‘variation is created’), and ‘Required’ and ‘Desirable’ are modal operators that change the meaning of the propositions they precede (‘it is required that . . .’, and ‘it is desirable that . . .’, respectively).

\(M\) and \(E\) can be understood as propositions describing means and end, respectively. Note that if the modal operators are removed, the resulting pattern of inference coincides with the one known as abduction, or ‘explanatory abduction’.26

The same abductive pattern underlies the justification of decision 31a, as can be seen by a similar analysis. Thus we have established that (from one point of view)
• it is desirable that detached houses are organized in the border zones traditionally along a road . . .

However, the backward decision 32a immediately discards decision 31a: ‘But too much of this will be monotonous’ [rep 32]. That monotony of the layout is undesirable is clearly implied by the protocol at this point. We hardly need to state explicitly the (rather trivial) underlying argument in order to see that it follows the pattern:

\[
\begin{align*}
\text{From} & \quad P \rightarrow Q \\
\text{and} & \quad \text{Desirable} \neg Q \\
\text{conclude} & \quad \text{Desirable} \neg P
\end{align*}
\]

(where ‘\(\neg\)' reads ‘not’). In plain English the conclusion of the argument is.

• it is desirable that detached houses are not organized in the border zones traditionally along a road . . .

Presumably, such a situation where a statement and its negation are both deemed ‘desirable’ (from different points of view) is quite common in design rationalization. Note that, judging from the protocol, the final decision (32a) was made without any attempt to compare the cogency of the two opposed justification arguments; indeed without leaving any trace of reasoning, despite the apparent rationality of the protocol.

3.3 Sample analysis: design knowledge elicited
A close reading of the protocol reveals reliance on general background knowledge. For example decision 15a (on the interconnection of the main pedestrian traffic channels which run roughly in parallel) relies on the rule of thumb that residential areas should be ‘permeable’ to pedestrians (see the design guide by Bentley et al27).

A more systematic search for such background knowledge can be undertaken using the same kind of logical analysis as illustrated in section 3.2. In constructing explicit rationalization arguments and insisting that they be logically coherent, one may encounter premises (tacitly or explicitly assumed in the protocol) that express background knowledge23,24.

3.4 Sample analysis: design evolution
Rudimentary though our replication protocol may be as evidence of truly
imaginative thought', we feel that an analysis of the protocol should be attempted in which we look for elements of 'design evolution' in the replicator's reasoning. We shall restrict ourselves here to the following two related observations, which we exemplify by reference to the protocol, and subsequently relate to the research literature.

Observation A: Given two decisions in the sequence of decisions identified in the protocol, the first one often specifies an END or goal to be achieved (deciding THAT), and the other MEANS to achieve it (deciding HOW).

Observation B: A given decision can be seen as specifying the means in relation to an earlier decision, and as specifying an end in relation to a later decision (which, in turn, provides the means to achieve that end).

On several occasions our decision sequence introduces a desirable situation, followed by an implementation of it in the context at hand ('deciding that' and 'deciding how', respectively). For example, decision 3a states that primary windbreaks be preserved, and decision 7a (to consider the strips of land 'ground', rather than 'figure') indicates how in the context created by decision 6a. On the other hand, decision 7a can also be seen as stating that the strips of land act as 'ground', and decision 7b as indicating how, namely by using the windbreaks as avenue trees, to 'unite' the buildings around them. A similar end-means relation holds between decision 7b on the one hand and decisions 8a and 8b on the other hand, which go into details of the avenue. Another clear example of an end-means relation is the one between decision 33a and decisions 34a-c, which introduce and 'implement', respectively, the idea of giving each legal category of housing its own physical expression.

Looking at the decision sequence in such terms of ends and means shows the strong connection between evolution and rationalization: to some extent, a how-decision is justified (a priori rationalized, as it were) by its very contribution to the implementation of a that-decision whose outcome is considered desirable (or required, e.g. if a given a priori by the brief as in the example in section 3.2).

Quite in keeping with our observation B, Eekels finds (in a context of design in general, but without reference to empirical material) that 'every end can be considered a means towards further or higher ends, and it virtually depends upon the level from where one looks to it whether a certain item is to be called a means or an end'28.
The ends and means (‘that’ and ‘how’) aspect of decisions has, surprisingly, an interesting parallel in the GARM model (see note 6) suggested by Gielingh as a way of structuring computerized ‘product models’. In GARM, products such as buildings are described in terms of product definition units (PDUs). A PDU is ‘any part of the product interesting enough to record information about’ (p 9). Various subtypes of PDUs are distinguished for various life-cycle stages of the product, from specification and design to demolition. In the present context, only two are of interest: functional units which are PDUs as required, and technical solutions which are PDUs as designed. In GARM, specification and design of a product is assumed to proceed basically in a top-down manner: requirements or constraints are attached to functional units which are decomposed into constituent technical solutions, which, in turn, must have characteristics adequate to satisfy the requirements and constraints. Technical solutions may contain further, smaller, functional units to which again technical solutions can be found, and so forth.

Gielingh’s functional units (with associated requirements and constraints) can be seen as expressing ends, and his technical solutions as providing the means to achieve those ends. But whereas functional units and technical solutions belong to separate classes, that-decisions and how-decisions do not; decisions, we contend, have a dual nature as both means and ends, depending, as we saw, on what other decisions they are related to. Yet the fundamental notion of design evolution as a search for means to achieve ends, with means giving rise to (or being seen as) new ends is common to Gielingh’s view of design and ours.

In a classical paper, Darke demonstrated how a number of practicing architects, rather than starting from ‘a full and explicit list of factors to be considered’ tended to ‘reduce the variety of potential solutions to the as yet imperfectly understood problem’ (p 186 of the 1984 reprinted edition), in order to make the problem cognitively manageable. They began their design process by concentrating on what Darke called a primary generator; described by her as ‘a particular objective or small group of objectives, usually strongly valued and self-imposed’. For example, designers may wish to ‘express the site, to provide for a particular relationship between dwelling and surroundings, to maintain social patterns, and the like’. One of the architects she interviewed described such a primary generator as follows: ‘... there were some good trees round the edge of the site. So we tended to put it [i.e., the building mass] in the middle, looking outwards. That was one of the generating things’ (p 183). Obviously, the decision of the Spangsbjerg design team to preserve the windbreaks is quite analogous, and a clear example of a
primary generator (though not entirely 'self-imposed' since it was actually mentioned in the design brief as desirable). Darke used her empirical evidence in an attempt to refute the then popular model of design as a process of 'analysis - synthesis', and proposed a 'generator - conjecture - analysis' model of design. The role of the primary generator, according to her model, is to provide the designer with 'a way in to the problem', giving rise to a conjectured solution 'which makes it possible to clarify the detailed requirements as the conjecture is tested to see how far they can be met' (pp 186–187).

Our case study, and in particular observation B, seems to suggest instead that Darke's 'primary generator' is merely the first in a series of decisions, each one of which serves to 'reduce the variety of potential solutions' and provide a 'way in' to what remains of the problem.

4 Conclusions

We have presented the method of replication protocol analysis (RPA), discussed it in a methodological perspective, and applied it to a specific case taken from architectural practice. To illustrate the use of RPA, the replication protocol generated from the case was analysed from three different points of view: that of design rationalization (justification of decisions), that of elicitation of design knowledge, and that of design evolution (the way in which chains of decisions are created). As the result of this, the following contributions have been made:

1) A step-by-step description of RPA. This may serve as a practical tool in design research or education (section 1.1)
2) A theoretical argument in favour of RPA as compared to other methods (section 1.2) and an assessment of its applicability (section 1.3). This is offered as a contribution to the methodological debate of design research
3) A replication protocol describing a fairly complex real-world design case (section 2) in a detailed yet compact form (see protocol excerpts in section 3.1; the complete protocol is also available22). The material may serve as raw data for further research
4) Insights into the nature of design thinking (obtained through the analyses presented in sections 3.2–3.4), notably about logical aspects of design rationalization, and a proposed generalization of Darke's classical result on 'primary generators'.

5 Acknowledgments

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Notes
1 If, as we believe, our assumptions express the essence of the passage by Lawson just quoted, one may wonder why, in his discussion of the four categories of methods, he appears to regard rationalization with such suspicion (see the introduction to section 1)
2 Originators of the project are: Lars Due, Michael Harrebek, Ole Nielsen, Erling Stadager, and Heige Tindal (Architects MAA), assisted by Ib V. Nielsen, Birgitte Henningsen, Jens Kvorning, Per Christensen, Søren Bisgaard, and Lars F. Nielsen (Architects MAA)
3 Note added after replication exercise: preservation of the windbreaks was mentioned in the brief as a desirable goal
4 In 'shared ownership housing' (Danish: 'andelsboliger') each household is entitled to the use of its dwelling, but shares ownership of it with other households
5 The figure-ground distinction is known from the psychology of perception. A famous example is the ambiguous picture of a vase-shaped figure on a dark ground, or of a figure like the profiles of two dark faces on a bright ground
6 GARM: 'General AEC reference model' where AEC stands for 'Architecture, Engineering, and Construction'. The account of GARM given here draws on a summary by Galle