Abstract—In this paper, we extend the set of library components which are usually considered in architectural synthesis by components with built-in chaining. For such components, the result of some internally computed arithmetic function is made available as an argument to some other function through a local connection. These components can be used to implement chaining in a datapath in a single component. Components with built-in chaining are combinatorial circuits. They correspond to “complex gates” in logic synthesis. If compared to implementations with several components, components with built-in chaining usually provide a denser layout, reduced power consumption, and a shorter delay time. Multiplier/accumulators are the most prominent example of such components. Such components require new approaches for library mapping in architectural synthesis. In this paper, we describe an IP-based approach taken in our OSCAR synthesis system.

I. MOTIVATION

Architectural synthesis (also known as high-level synthesis (HLS)) can be defined as the task of implementing a given behavioural specification by means of an appropriate register-transfer (RT-) level architecture. Architectural synthesis is considered to provide the next productivity boost for designers of information-processing devices.

RT-level components, which have been considered so far, include registers, register-files, busses, multiplexers and multi-functional units (ALUs). All functional units were considered to compute essentially a single (possibly control-selectable) standard function, such as addition, subtraction, or multiplication. On the other hand, current component libraries contain a growing number of components with built-in chaining (BIC) or internal chaining. With built-in chaining, the result of some computed standard function is made available as an argument to another function. For example, multiplier/adders multiply two numbers and add the result to a third one (see fig. 1). With BIC components, chaining in HLS can be implemented by a single component. In contrast, standard chaining requires external wiring between two or more components (therefore, we call it external chaining).

In addition to multiplier/adders, multiplier/adder/accumulators (MACs), ALUs followed by (internal) shifters, and adders followed by (internal) comparators are components with internal chaining.

The main advantages of such components include:

- **The ability to generate efficient layout.** The layout of BIC components is usually more efficient than the combined layout of several independently designed functional units. For example, abutment of corresponding lines may be possible.

- **Delay and power consumption may be smaller than for separate components.** The delay of BIC components may be small due to a) the more compact layout, b) exploitation of context-dependent information during logic synthesis, and c) adjustment of the strength of drivers.

- **Design-reuse of complex components is facilitated.** Exploiting the presence of BIC components is important for re-using available valuable designs.

Example:

Table 1 shows area, delay times and power consumption of adders, multipliers, and multiplier-adders, respectively. The same information

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### Table 1: Area, power, and propagation delay for commercial library components

<table>
<thead>
<tr>
<th>Cell</th>
<th>Area [((kλ)^2)]</th>
<th>Power (@ 8 MHz) [mW]</th>
<th>Propagation delay [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>adder (64 Bit)</td>
<td>5.410</td>
<td>unknown</td>
<td>18.44</td>
</tr>
<tr>
<td>multiplier (32 Bit)</td>
<td>14.717</td>
<td>20.286</td>
<td>107.76</td>
</tr>
<tr>
<td>multiplier-adder-cell (32/64 bit) (built-in, internal chaining)</td>
<td>15.312</td>
<td>20.832</td>
<td>108.65</td>
</tr>
<tr>
<td>multiplier-cells + adder-cells (external chaining) (32/64 bit)</td>
<td>36.585</td>
<td>unknown</td>
<td>117.66</td>
</tr>
</tbody>
</table>

The behavioural specification of digital signal processing architectures can be represented by *data-flow graphs (DFGs)*. Fig. 3 shows the DFG of the well-known elliptical wave filter and indicates where multiplier/adders can be used. It is obvious that quite a number of operations can be implemented by multiplier/adders.

II. Previous Work

In HLS synthesis, there has been only a very limited amount of work which took BIC components into account.

Work on the Cathedral silicon compilers (see e.g. [7]) is one of the few contributions to the area. The execution unit (EXU) model of Cathedral includes BIC. However, only an essentially fixed number of EXU types has been considered and no results are known which contribute to the topic of the paper.

Research at the University of Eindhoven is directed at creating regular layouts from netlists in which regularity is not immediately obvious [8]. As a special case, these algorithms would be able to create a regular layout if, for example, an adder follows a multiplier in the netlist. However, the approach does not include exploitation of BIC components in HLS.

In logic synthesis, the situation is different. So-called complex gates have been used in library mapping for many years (see [5] as an example).
III. THE PROBLEM

In order to support BIC components in HLS, several issues have to be considered. Let’s start with an example to make these issues clear. Fig. 4 shows a section of a dataflow-graph (DFG).

Assume that a library containing adders, multipliers and multiplier/adders is given. There are several options for implementing this section of the DFG:

1. Implement + and * with two separate components in different control steps.

2. Implement + and * with two separate components in a single control step using standard chaining.

3. Implement + and * with a multiplier/adder in a single control step.

4. Implement + and * with a multiplier/adder performing a multi-cycle operation.

Clearly, decisions have to take many factors into account: delay, cost (power and area), intended clocking frequency, predicted wiring delays, and surrounding operations. Also, one might want to consider testability and error-recovery aspects of the different design options [3].

In this context, it has to be mentioned, that well-established standard techniques in HLS have to be revisited:

1. Scheduling and resource assignment can be modelled by functions taking DFG nodes (operations) as arguments and returning the corresponding control step and resource. In the context of BIC components, it is sometimes more adequate to use sets of nodes or operations as arguments.

2. The function performed by a component can no longer be described by a single operation identifier or an expression involving such a single identifier. Rather, expressions including several operation identifiers are required.
IV. APPROACH TAKEN IN OSCAR

A. Naming conventions

For our HLS system OSCAR (Optimum simultaneous scheduling, allocation and resource assignment), the ability to consider BIC components has been a major design goal. A very essential part of this is to select components for the final architecture. We use binary decision variables for modelling the selection of certain components:

\[ b_k = \begin{cases} 
1, & \text{if instance } k \text{ is selected} \\
0, & \text{otherwise} 
\end{cases} \] (1)

Each \( k \in K \) denotes a potential instance of a library element type \( m \in M \). Before synthesis is started, a sufficient set of instance identifiers is made available for each \( m \in M \). Fig. 5 is a graphical representation of naming in our model.

We distinguish between behavioural and structural domains. For each of these, we distinguish between types and instances. Specific types and instances are denoted by elements taken from sets of discrete elements. In actual implementations, sets of integers are used. In the paper, we are sometimes using sets of characters in order to improve readability. As can be seen from fig. 5, the sets for operation instances, operation types, component instances and component types are denoted by \( J, G, K, \) and \( M \), respectively.

Component functionality is modelled by relation executable on.

\[ \text{Def.: } \forall j \in J, k \in K : j \text{ executable on } k \iff k \in K \text{ is able to perform operation } j \in J. \]

We assume that all components are only able to start a limited number of operations. More precisely, we assume that component \( k \) is able to start a new operation after \( \ell(j, k) \) control steps if \( j \) is the operation most recently started. \( \ell(j, k) \) is called the component data initiation interval (dii).

Let \( G' \) denote the set of standard operations which are supported for an HLS system. In the case of OSCAR, \( G' \) corresponds to operations described in standard synthesis packages such as [9]. These operations can be represented by expressions containing single operation identifiers, for example "+" and ".". These operations are called simple operations.

In addition to these operations, OSCAR considers complex operations or macro operations, operations which can be performed by BIC components. If, for example, the library contains a MAC, then \((\text{in1} \cdot \text{in2}) + \text{in3})\) will be considered as a complex operation. Let \( G' \) denote complex operation types.

\[ \text{Def.: } G = G' \cup G'', G \text{ denotes the set of all operation types.} \]

Operation instances corresponding to \( G, G' \) and \( G'' \) are denoted by sets \( J, J' \) and \( J'' \), respectively.

In OSCAR, complex operations in the DFG are labelled just like simple operations (see fig. 4). Note that a certain node in the DFG may belong to several labels, to one for the node as a simple operation and possibly also to others if it is an element of complex operations.

The essential task of HLS is to establish bindings between operation and component instances. Moreover, most HLS algorithms also generate bindings to control steps at which these operations are started. In OSCAR, control steps are represented by integers \( i \) from an index set \( I \). Bindings are represented by decision variables \( x \). In the case of predefined instance bindings or cost functions containing interconnect costs, OSCAR uses triple-indexed decision variables with the following definition:

\[ x_{i,j,k} = \begin{cases} 
1, & \text{if operation } j \text{ is started on component instance } k \text{ at control step } i \\
0, & \text{otherwise} 
\end{cases} \] (2)

For each operation \( j \in J \), \( R(j) \) denotes the set of control steps during which \( j \) could be executed. \( R(j) \) can be computed by a simple ASAP/ALAP analysis or by techniques taking resource constraints into account.

B. The model

For a given component library, the cost function is a linear function of these variables.

\[ \sum_{m \in M} (\text{Costs}(m) \star \sum_{\substack{k \in K \\mid \ell(j,k) \equiv m}} b_k) \] (3)

This cost function is minimized under constraints describing correct solutions. The following constraints are not affected by the need of modelling BIC (see [6] for detailed equations):

1. Timing constraints:
   these constraints can be used to specify minimum and maximum delay between operations. Applied on read/write-operations it allows to meet given timing specifications.

2. Precedence constraints:
   These constraints reflect that operations cannot be started before their arguments have been computed.

3. Chaining constraints
   These constraints reflect the fact that the total combinatorial delay of the design should not exceed a given threshold. In OSCAR, we assume that such a threshold is known during the design process. An outer loop can be used to find a good threshold [4]. Using this threshold, OSCAR generates constraints in case the combined delay of data-dependent operations exceeds the threshold.
Resource assignments constraints guarantee that generated solutions respect the minimum data initiation interval. In our model, all results are generated in order to avoid solution 2 of section 3 in case high clocking frequencies have been specified. These constraints are not part of any other IP-model we are aware of.

Other constraints are affected by the need to model BIC:

5. Operation assignment constraints

These constraints reflect the fact that each operation has to be performed by a suitable hardware resource. This is guaranteed by the following constraints:

\[
\forall j' \in J': \sum_{i \in R(j')} \sum_{j \in \text{exec on } k} x_{i,j',k} + \sum_{j'' \in \text{exec on } k} x_{i,j'',k} = 1 \tag{6}
\]

The meaning of these constraints is as follows:

Each simple operation \(j'\) has to be implemented. There are two ways of doing this:

a) \(j'\) is implemented individually. In this case, the sum of \(x_{i,j',k}\) over all possible control steps \(R(j')\) and all components will be 1 (1st term in (6) = 1).

b) \(j'\) is implemented as part of a macro operation \(j''\). \(j'\) may actually be part of several macro operations, but only one of these can be implemented as a macro operation. Hence, the sum of \(x_{i,j'',k}\) over all macro operations \(j''\) enclosing \(j'\), over all control steps \(R(j'')\), and over all resources \(k\) capable of executing \(j''\) must be one (second term in (6)).

Example:
Let us assume that \(R(+) = 3, R(*) = 2, R(\odot) = [2..3]\). Then, the following equations will be generated:
\[ j^\prime = * : x_{2m} + x_{2M} + x_{3M} = 1 \quad (7) \]
\[ j^\prime = + : x_{3+a} + x_{2M} + x_{3M} = 1 \quad (8) \]

These equations guarantee that either the macro operation \( \circ \) or the simple operations will be bound to a hardware component.

By considering simple operations as a special case of macro operations, it would be possible to use just the right term of equation 6, but this would lead to some redundant computations.

V. RESULTS

In the following, we will describe our results for two standard examples: the elliptical wave filter (EWF) and an edge-detection algorithm. All results use the components described in table 1. The cycle time has been set to 50 ns in order to allow a controller and multiplexer delay of about 34 ns for single-cycle adds. For this cycle time, multiplications and multiply/adds will always be multi-cycle operations.

None of the results uses external chaining. Hence, the following tables mainly demonstrate the effect of built-in chaining. The execution times have been measured on a SPARC 20 using the mixed IP-solver \texttt{lp.solve} [1].

Tables 2 and 3 show the results for the elliptical wave filter.

Table 2: Results for EWF without BIC components

<table>
<thead>
<tr>
<th>cs</th>
<th>add</th>
<th>mult</th>
<th>active area ([k \lambda]^2)</th>
<th>runtime [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>3</td>
<td>4</td>
<td>66.083</td>
<td>\leq 1</td>
</tr>
<tr>
<td>21</td>
<td>2</td>
<td>3</td>
<td>48.961</td>
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</tr>
<tr>
<td>22</td>
<td>2</td>
<td>2</td>
<td>34.244</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3: Results for EWF with BIC components

<table>
<thead>
<tr>
<th>cs</th>
<th>add</th>
<th>sub</th>
<th>mult</th>
<th>active area ([k \lambda]^2)</th>
<th>runtime [s]</th>
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<tbody>
<tr>
<td>17</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>67.872</td>
<td>\leq 1</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>50.154</td>
<td>37</td>
</tr>
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<td>19</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>35.434</td>
<td>216</td>
</tr>
</tbody>
</table>

Tables 4 and 5 show the results for the edge detector algorithm.

Table 4: Results for edge detector without BIC components

<table>
<thead>
<tr>
<th>cs</th>
<th>add</th>
<th>sub</th>
<th>mult</th>
<th>active area ([k \lambda]^2)</th>
<th>runtime [s]</th>
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</thead>
<tbody>
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<td>2</td>
<td>8</td>
<td>127.418</td>
<td>\leq 1</td>
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<tr>
<td>13</td>
<td>2</td>
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<td>7</td>
<td>112.700</td>
<td>\leq 1</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>68.548</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 5: Results for edge detector with BIC components

<table>
<thead>
<tr>
<th>cs</th>
<th>add</th>
<th>sub</th>
<th>mult</th>
<th>active area ([k \lambda]^2)</th>
<th>runtime [s]</th>
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</table>

VI. CONCLUSION

In this paper, we have proposed to pay attention to the need of modelling components with built-in chaining (BIC). We have stressed the importance of the support of these components in high-level synthesis. As an example, we have shown how BIC can be modelled in integer-programming (IP) based synthesis
algorithms. IP-models provide a basis for adding support for BIC in a rather straightforward way. Due to recent advances in IP-based modelling, we have been able to generate designs in acceptable computation time [6].

These results demonstrate the efficiency of designs using BIC.

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REFERENCES


