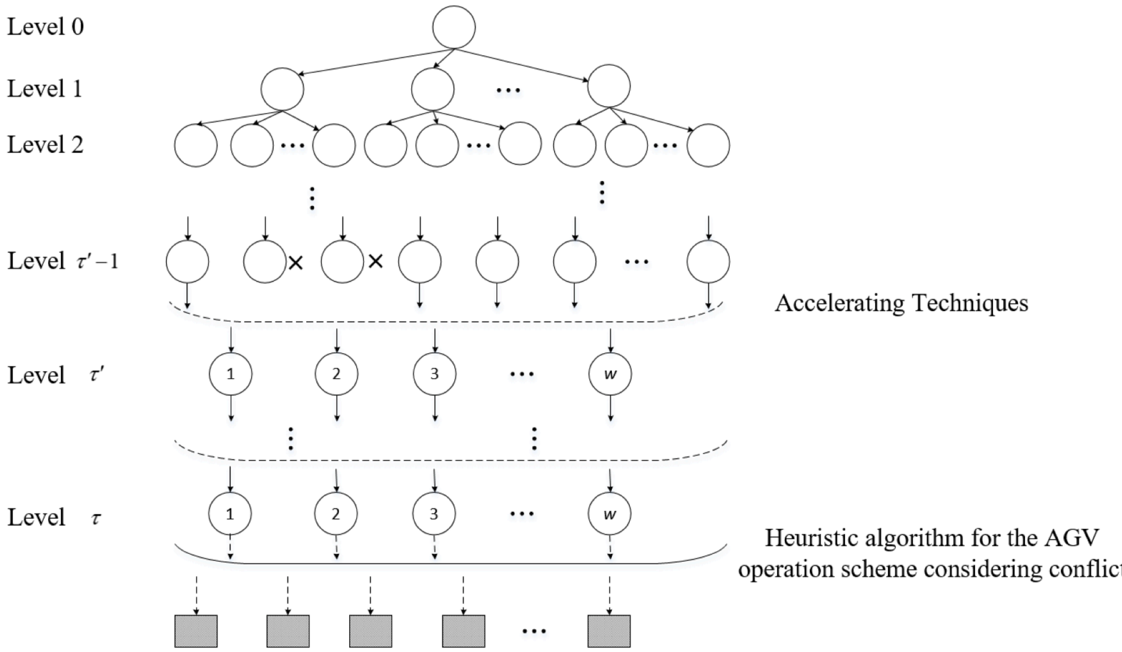

Fig. 8. The structure of the B&B algorithm.

(iv) **Time constraints.** The time constraints ensure the time relationship of the QC and the AGV to operate containers. Constraint (29) ensures the time relationship of the QC operation, and constraints (30), (31), (34) to (36) ensure the time relationship of the AGV to transport a container. Constraints (32) and (33) ensure the time relationship of the AGV to transport two consecutive containers. Fig. 7 shows the time relationship between the variables, which can be used to understand the time constraints. In Fig. 7, (m,i) is an unloading container and (n,j) is a loading container. The time constraints of AGV actions can be explained as follows. Constraint (29) ensures that the quayside operation is under the given job sequence for each QC. Constraint (30) ensures the loading and unloading sequences of containers on the ship for QC operation, and constraint (31) ensures the sequences of containers in the yard for ASC operation. Note that containers (m,i) and (n,j) in set ψ_2 are located in the same block. Constraints (32) and (36) ensure the minimum time gap between the yard side operation and AGV action for the AGV to transport a container. Constraints (33) and (37) ensure the minimum time gap between the quayside operation and AGV action for the AGV to transport a container. Constraints (34) and (35) ensure the minimum time gap between the AGV action and quayside (or yard side) operation for the AGV to transport two consecutive containers. Constraint (38) models the minimum time gap between two sequential actions. Constraints (39) to (41) model the relationship between intermediate variables and decision variables, which are used to link variables $P^{X}_{(m,i,\alpha),x}$ and $P^{Y}_{(m,i,\alpha),y}$ with $t^{AGV}_{(m,i,\alpha_1)(n,j,\alpha_2)}$.

$$T^{Start}_{(n,j,\alpha_2)} + M\left(1 - U^{AGV}_{(m,i,\alpha_1)(n,j,\alpha_2)}\right) \geq T^{Start}_{(m,i,\alpha_1)} + t^{AGV}_{(m,i,\alpha_1-1)(m,i,\alpha_1)}, \forall (m,i,\alpha_1),(n,j,\alpha_2) \in W^{T} \tag{38}$$

$$T^{Q}_{(m,i+1)} \geq T^{Q}_{(m,i)} + G^{Q}_{(m,i)} + S^{Q}_{(m,i)(m,i+1)}, \forall (m,i),(m,i+1) \in C \tag{29}$$

$$T^{Q}_{(n,j)} \geq T^{Q}_{(m,i)} + G^{Q}_{(m,i)}, \forall (m,i,n,j) \in \psi_1 \tag{30}$$

$$T^{Y}_{(n,j)} \geq T^{Y}_{(m,i)} + G^{Y}_{(m,i)}, \forall (m,i,n,j) \in \psi_2 \tag{31}$$

$$T^{Y}_{(m,i)} \geq T^{Start}_{(m,i,3)} + t^{AGV}_{(m,i,2)(m,i,3)}, \forall (m,i) \in D \tag{32}$$

$$T^{Q}_{(m,i)} \geq T^{Start}_{(m,i,3)} + t^{AGV}_{(m,i,2)(m,i,3)}, \forall (m,i) \in L \tag{33}$$

$$T^{Y}_{(n,j)} + M\left(1 - \sum_{l \in B} Z_{(m,i)(n,j),l}\right) \geq T^{Start}_{(m,i,4)} + t^{AGV}_{(m,i,3)(m,i,4)}, \forall (m,i) \in D, \forall (n,j) \in L \tag{34}$$

$$T^{Q}_{(n,j)} + M\left(1 - \sum_{l \in B} Z_{(m,i)(n,j),l}\right) \geq T^{Start}_{(m,i,4)} + t^{AGV}_{(m,i,3)(m,i,4)}, \forall (m,i) \in L, \forall (n,j) \in D \tag{35}$$

$$T^{Start}_{(m,i,\alpha)} \geq T^{Y}_{(m,i)} + G^{Y}_{(m,i)}, \forall (m,i) \in D, \alpha \in \{4\} \; or \; \forall (m,i) \in L, \alpha \in \{1\} \tag{36}$$

$$T^{Start}_{(m,i,\alpha)} \geq T^{Q}_{(m,i)} + G^{Q}_{(m,i)}, \forall (m,i) \in D, \alpha \in \{1\} \; or \; \forall (m,i) \in L, \alpha \in \{4\} \tag{37}$$

$$X^{position}_{(m,i,\alpha)} = x, P^{X}_{(m,i,\alpha),x} = 1, \forall (m,i) \in C, \forall \alpha \in \{0,1,2,3,4\}, \forall x \in X^{R} \tag{39}$$

$$Y^{position}_{(m,i,\alpha)} = y, P^{Y}_{(m,i,\alpha),y} = 1, \forall (m,i) \in C, \forall \alpha \in \{0,1,2,3,4\}, \forall y \in Y^{R} \tag{40}$$